INTEGRATED INFORMATION DISPLAY TO SUPPORT ICU NURSES AT THE BEDSIDE: ETHNOGRAPHIC OBSERVATION, DESIGN, AND EVALUATION

by

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ABSTRACT

Preventable adverse events are one of the leading causes of hospitalized patient deaths. Many of these adverse events occur in Intensive Care Units (ICUs) where nurses often work under cognitive, perceptual, and physical overloads. Contributing to these overloads are spatially separated devices which display treatment relevant information such as orders, monitoring information, and equipment status on numerous displays. If essential information of these separate devices was integrated into a single display at the bedside, nurses could potentially reduce their workload and improve their awareness of the patients' treatment plans and physiological status.

We conducted a set of three studies for the purpose of designing an efficient and effective ICU display. We observed ICU nurses during their shifts and found that task-relevant information was often presented in the wrong format, unavailable at the point of care or laborious to obtain. Additionally, nurses were sometimes unaware of significant changes in their patient's status and equipment operation. Based on nurses' feedback, we designed an integrated information display that presents all of the information that nurses need at the patient bedside. Nurses selected a display based on the information organization of existing patient monitors, with added medication management and team communication features. The evaluation of paper-based prototypes of both the integrated display and existing ICU displays showed that nurses could answer questions about the patient's status and treatment faster ($p<<0.05$) and more accurately ($p<<0.05$) using the integrated display. The number of adverse events in the ICU could potentially be reduced by integrated displays, but to implement them into clinical practice will require significant engineering efforts.

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CHAPTER 1

INTRODUCTION

Medical errors in ICUs

Medical errors occur frequently and can result in significant harm to patients. A high number of deaths in US hospitals have been attributed to preventable adverse events.[1] Patients at Intensive Care Units (ICU) are especially at risk for medical errors.[2] In ICUs errors occur frequently – during 1000 ICU patient days 146 serious errors were identified.[3] A portion of the errors could be attributed to ICU nurses' significant cognitive overload[4] and distractions, such as constant interruptions during the care process.[5] Adding to the cognitive overload is the excessive information nurses receive from various sources, such as multiple individuals working in the same space and multiple bedside displays.[4]

Also, contributing to the cognitive overload are bedside displays with poor ergonomics.[6] They are too small,[7] have poor labeling,[4] and do not meet users cognitive requirements.[8-10] Such devices show information hidden in complicated menu structures,[9] are unintuitive to use[6, 11, 12] and are difficult to learn.[13, 14]

Another factor which increases cognitive overload is the piecemeal fashion in which nurses need to collect task relevant information from a multitude of different devices, screens and locations. Such disparately located information makes getting the "big picture" difficult.[6] Currently clinicians spend a great deal of time and energy searching through raw data trying to understand the patient's situation.[10] Their decision making is hindered through ill-structured, uncertain, and potentially confliction information from multiple sources.[15] Half of all critical incidents that occur in ICUs can be attributed to low situation awareness, with the other half due to low technical skills.[16]

Situation awareness was defined by Endsley[17] and is a theory which can guide research about the user's understanding of the environment. It includes three levels: (i) perception, (ii) comprehension and (iii) projection.[10, 85-89] The Background section discusses situation awareness further. Improved display of information could improve nurses' decision making and situation awareness.

Suggestions to decrease medical errors

Suggestions to decrease errors in critical care are improvements in the user interface for medical devices, automated error checks, salient alarms, and in-service training.[8] Another suggestion is the consolidation and integration of all relevant information in one place.[18]

Used by ICU nurses, such integrated displays "hold tremendous promise for improving patient care."[19] The integration of separate information from a variety of sources into one place can improve medical decisions and treatment.[18] Integrated information would allow nurses to better understand the effectiveness of interventions and the patient's response to them.[9]

In other areas integrated information displays have been shown to increase the operator's situation awareness in anesthesia,[20] power plant management,[21] air traffic control,[22] and might increase shared understanding among care providers.[23] Displays developed to support specific care aspects were found to partially increase provider's accuracy, time efficiency, and situation awareness, e.g., [6, 20, 24-33] - the background section will discuss issues in more detail.

However, to increase nurses' situation awareness at the point of care, a better understanding of nurses' information needs in clinical decision making is needed,[34] and what information is missing during clinical tasks.[35] No research could be identified that reported detailed descriptions of an integrated information display for ICU nurses based on all relevant nursing tasks at the bedside.

Missing information to develop an integrated display

An integrated display should address current information deficits ICU nurses have during frequent and patient safety critical tasks. Although some publications list frequent tasks performed by ICU nurses,[36-38] they do not list specific information nurses need during these tasks. Furthermore, although publications identified errors during ICU nursing care, e.g., [11, 39, 40] patient safety ratings for single nursing ICU nursing tasks could not be found.

To develop an integrated display for the ICU bedside, relevant nursing tasks need to be identified, and the key information to be shown. Detailed information deficits during frequent and patient safety in nurses' situation awareness need to be identified and mitigation strategies need to be implemented. Finally, the display needs to be evaluated.

Specific aims

Improvements of the work environment of ICU nurses are needed, as nurses spend the most time of all health care team members in the patient's room.[36] Our research attempted to further the understanding of the complex information needs nurses face at the bedside with a focus on challenges during frequent and safety relevant tasks at the bedside, and to design and evaluate an integrated information display addressing these challenges.

Aim 1: Identify requirements for an integrated information display for ICU nurses at the bedside. The first aim of this investigation was to acquire information about critical care nurses' work through observation of the tasks nurses perform (Chapter 3). Objectives were a) to identify frequent nursing task categories and their associated information, b) to identify patient safety critical task categories, and c) to create a vision for an integrated display.

Aim 2: Develop the integrated information display and refine user requirements. The second aim was to design an integrated information display to support frequent and patient safety critical nursing tasks at the bedside (Chapter 4). Objectives were a) to identify nurses' preferred information organization and information content for an integrated display, and b) to improve intuitiveness and correct extraction of information.

Aim 3: Evaluate the integrated information display. The third aim was to assess nurses' performance when using the new information display compared to using conventional control devices (Chapter 5). Objectives were to measure their a) situation awareness, b) response time, c) workload, and d) satisfaction.

CHAPTER 2

BACKGROUND

ICU nurses' patient care activities

ICU nurses are responsible for the monitoring and detection of changes in physiological functions on a minute-by-minute and hour-by-hour basis.[41] Patient monitoring is only one of multiple functions ICU nurses perform. They also must document their work, give medications and support care coordination.[38] Hendrich, et al.[38] found that medical surgical nurses spent 78% of their time with nursing practice. During nursing practice they were found to spend 7% of their time in patient monitoring - patient assessment and reading of vital signs. More time consuming were documentation (35%), care coordination (20%), patient care activities (19%), and medication administration (17%). Therefore, nursing practice tasks might benefit from additional support.

ICU nurses' patient monitoring might be improved through better support of tactical monitoring. Miller et al.[41] found that nurses were more interested in shorter timeframes and attended to perceived information with a rather tactical orientation. Doctors, on the other hand, preferred attending to strategic information with focus on future patient projection and a broader range of physiological functions than nurses. Miller et al. [41] hypothesize that the traditional nursing role might contribute to their focus on short-term changes in the patient's physiological values. Overall, nurses' patient monitoring might benefit from devices which emphasize tactical monitoring.

In a study about information on displays to support nurses' patient monitoring, the variables that ICU nurses determined to be the most important were in the cardiovascular, respiratory, fluids, and temperature domains.[42] In cardiovascular monitoring they identified heart rate, arterial blood pressure, vasoactive drug infusion rates, central venous pressure, and pulmonary capillary wedge pressure. In respiratory monitoring, they determined mode of ventilation, artificial ventilation rate, spontaneous ventilation rate, minute volume, O_2 saturation, fractional inspired oxygen, as well as peak and expiratory pressure. For fluid management, nurses desired the cumulative and hourly fluid balance, hourly fluid input and output, and hourly urine and non-urine output. To support their awareness of temperature, nurses wanted core and peripheral (skin) temperature.

Few of the studies listed above use a conceptual model to guide identification of information needs. The model developed by Endsley identified situation awareness as key to effective performance. This model is described below.

Situation awareness

Situation awareness is a theory which can guide research about the operator's understanding of the state of the environment and of relevant parameters of the system.[10, 85-8917] According to Endsley,[17] situation awareness includes three levels: (i) perception, (ii) comprehension and (iii) projection, see Figure 1. Success at the higher levels depends on the success of the lower levels. *Perception* means that the user is aware of the current state of the system e.g., a variable of the system - a nurse might see the systolic value of the blood pressure. *Comprehension* refers to the user's understanding of implications of

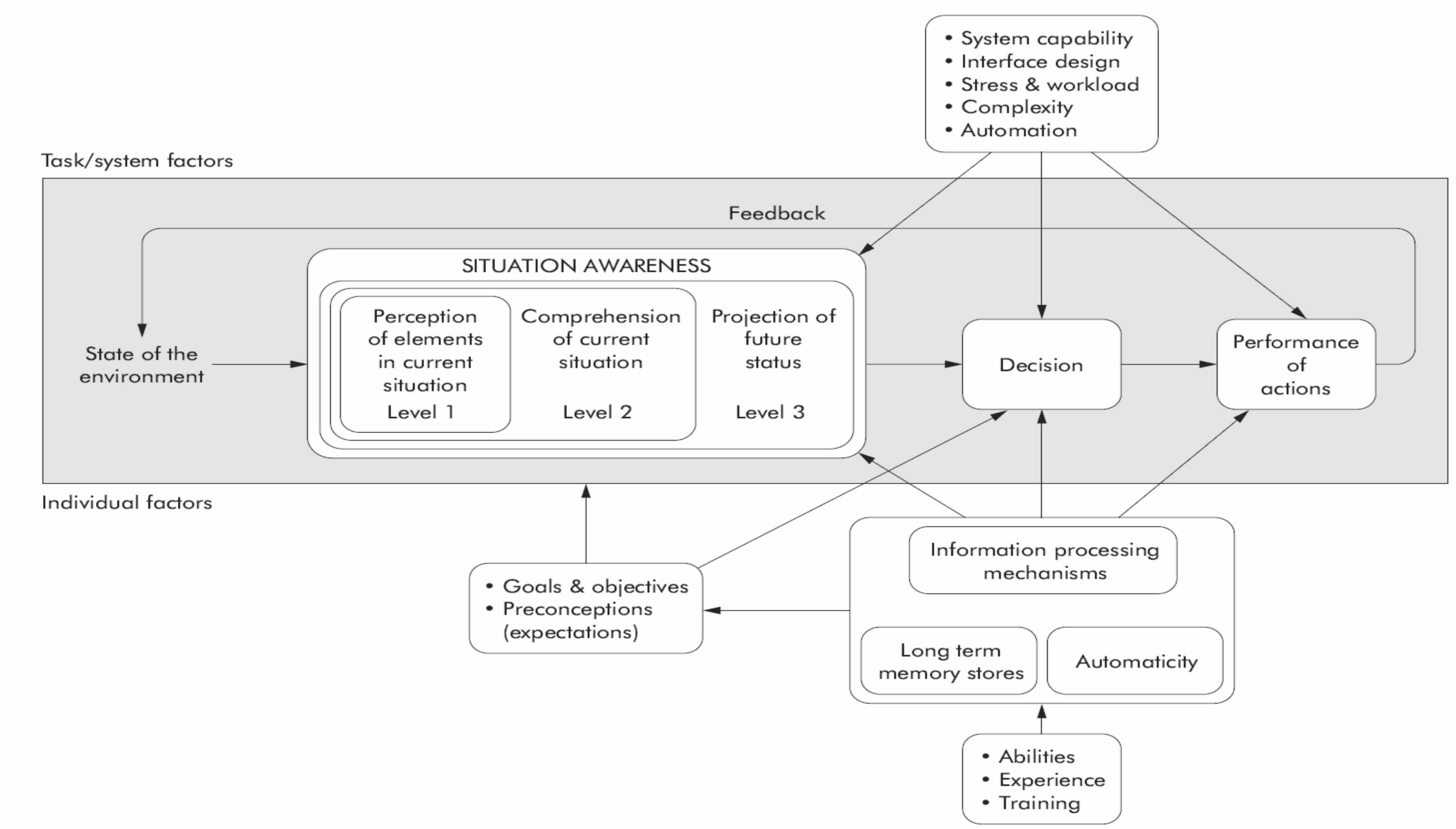

Figure 1: Model of situation awareness (Endsley 1995).
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the perceived values of the system e.g., the meaning of the variable – a nurse might understand that the blood pressure is lower than it should be, considering the patient's condition. *Projection* depicts the user's anticipation of consequences for the system and its future development, e.g., the implication of a variable – a nurse might anticipate that if nothing changes in the renal function of the patient, he could be impaired through the current condition. The level of situation awareness influences decisions and performance of actions.

In Endsley's model (Figure 1) situation awareness is influenced by both individual factors and task/system factors. Individual factors which influence situation awareness include the user's goals, expectations, information processing mechanisms, abilities and training. Task/system factors are system capacity, interface design, stress and workload, complexity, and automation. An integrated information display could address problems in interface design, complexity of the system and automation and possibly reduce stress and workload.

In accidents attributed to human error, inadequate situation awareness has been identified as a primary causal factor.[90] Situation awareness is diminished by the large number of data elements which operators need to monitor and combine in their heads, resulting in decreased cognitive resources available to attend to important events.[10]

In medical decision making, situation awareness is a critical component, and the level of situation awareness acquired by a practitioner may be critical to the outcome of the patient.[91] Clinicians' inadequate awareness of data may lead to insufficient comprehension of the patient status.[92]

Increasing the user's situation awareness has become a major goal in the development of user interfaces in a variety of fields. Integrated information displays have been shown to increase the operator's situation awareness in anesthesia,[20] power plant management,[21] air traffic control,[22] and might increase shared understanding among care providers.[23] In the evaluation of displays for nurses no report of situation awareness was found – but accuracy and detection of changes were measured which might be used to operationalize situation awareness at the bedside.

Comparison with other human computer interaction models

The model of situation awareness is compared with two other models which describe human computer interaction: the Staggers health human-computer interaction framework[43] and the model by Despont-Gros[44] to evaluate user interaction with clinical information systems.

In a temporal dimension the model of situation awareness has shortcomings compared with other human computer interaction models - the situation awareness model is missing a temporal component. In Staggers' model the temporal component is called "informatics development trajectory", in Despont-Gros's model it is called "development process". In these models it is used to describe changes and maturation of user characteristics or interaction. One of these user characteristics is training: users gained more experience with systems when getting used to them and were found to prefer a higher information density after sufficient training.[45]

On the dimension of user characteristics the situation awareness model has the highest level of detail. It cites the individual factors goals, objectives, expectations, individual information processing, memory, automaticity, abilities, experience and training are taken into consideration. The other two models do not go into detail. Similarities exist in the three models in the description of the user interaction with the system.

Environmental and computer system characteristics are described in all three models, with the situation awareness analyzing them in the highest level of detail. For system characteristics, the situation awareness model takes task and system factors into consideration: system capacity, interface design, stress, workload, complexity, and automation. The other two models go into less detail. Staggers' model shows computer characteristics and actions. Despont-Gros's model has computer information system, environment and process characteristics but does not specify them further.

For our research situation awareness seems to suits best as conceptual model. As our research aims to change the information presentation and availability for nurses, it influences environmental and computer system characteristics. Therefore, these system characteristics need to be shown in detail – in the way they are described in the situation awareness model. Although the missing temporal component of the model is a shortcoming, the greater level of detail in environmental characteristics should provide more benefit.

To increase the operator's understanding of devices and possibly the situation awareness, devices can be designed more intuitively, e.g. by applying human factors design principles.

Human factors screen design principles

The application of human factors principles increases intuitiveness and user friendliness of medical devices.[7, 46] Shneiderman[47] defined 8 golden design rules, Zhang et al.[48] 14 usability heuristics for medical devices, and Drews et al.[22] summarized human factors design principles. Among these rules, heuristics and principles are a) proximity of related information, b) redundant coding, c) gestalt principles, d) high saliency, e) congruence with mental models, f) affordances, g) pictorial realism, h) direct manipulation, i) labeling in the users' terminology, j) addressing individual users' characteristics, k) flexibility and efficiency, l) minimalist information, and m) consistency of action. These principles are explained in the following, and illuminated with possible implications for the design of information display for nurses.

Proximity of related information

The display of related information in proximity to each other facilitates cognitive processing of information.[49, 50] A display can show related information integrated in spatial proximity – e.g., all medication could be shown in the same display area. The two options for data integration are first, integration into a single display and second, integration into a single display element. First, data integration into a single display describes the consolidation and combination of multiple data sources into a single interface - one of the cornerstones of biomedical informatics according to Stead et al.[18] Second, the integration of multiple data sources into a single display element is a variant for "integral display".[51] Here the graphical representation of a single display element is altered to visualize changes in multiple variables, e.g., through simultaneous change of color and brightness.

Redundant coding

Redundant coding of information shows data in more than one dimension to improve identification.[7] In a device, color and symbols could be used for redundant coding – e.g., a specific color and symbol can be used to redundantly communicate the same message.

Gestalt principles

The gestalt principles allow humans to see things as belonging together when they are in spatial proximity, move together, or look alike in color, size, or shape.[52] For example, on a display the users can be cued to understand that information belongs together by using similar looking display elements in spatial proximity (proximity principle).

High saliency

High saliency of relevant information facilitates the search processes.[53] For example, an interface can use color coding in red to increase the saliency of important information such as alarms because it is not common and bright.

Congruence with mental models

To facilitate understanding, the information organization should reflect the user's mental model[11]. A mental model is the internal representation of some aspects of the external world used to make predictions and inferences.[54] To assess mental models of user interaction with a device, users can be asked for their expectations prior to pressing a button on the device. The final interaction can then be designed according to their mental model of the interaction.

Affordances. Affordance refers to the cues provided by the environment that indicate an opportunity to act or perform a particular operation. For example, a door handle provides an affordance to pull and a big red button invites "pushing."[53]

Pictorial realism

The information on the display should have the appearance of the variable presented by it (pictorial realism) and dynamically displayed information should reflect the users' mental model about the movement in the real system(principle of moving parts).[55] To design for pictorial reality, a device should communicate a real world variable, it should look similar to the depicted value, e.g., time could be visualized by an hour-glass. To satisfy the principle of moving parts, a value which is decreasing should move down on the display.

Direct manipulation

Direct manipulation of visible objects on the graphical user interface enhances usability.[11] A device could have a touch-screen which allows the user to directly select which displayed variables to interact with.

Labeling in user's terminology

Labeling in the users' terminology shortens learning.[48, 53] A display for nurses should not have abbreviations but label displayed variables in terms nurses use in their daily life. Observing nurses and asking them about their understanding of prototypes could identify this terminology.

Congruency with user's characteristics

Designs should address individual user characteristics. [11, 14, 48, 56] A display for nurses should show information which is relevant for this user group, instead of designing devices which satisfy the information needs of nurses, physicians, and respiratory therapists simultaneously.

Flexibility and efficiency

To accelerate performance and accommodate for differences between users, systems should allow customization and shortcuts.[47, 48] A display for nurses could allow different ways to get to the same goal and customization of information content

Minimalist information

Extraneous information distracts and slows users down, and simple or sparse information should be used with progressive levels of details.[48] On an information display the initial screen could show only essential information and should reveal more information upon interaction.

Consistency of action

Consistent sequences of actions should be possible in similar situations. Menus, help screens, and commands should use identical terminology.[47] A display for nurses should e.g. allow manipulating all different kinds of medication with the same actions – independent if they are current, scheduled or PRN medication.

In conclusion, during the design phase we introduce the above principles gradually. By following the above design principles, when designing a display for nurses, it can be assumed that the resulting device is more usable, is easier to understand and more desirable for nurses. However, not all of principles can be incorporated into the design process in very early prototype stages but need to be introduced after the prototypes have reached a certain maturity. Such principles are for example consistency of action, flexibility, and efficiency.

Designing a device in cooperation with the final users ensures that information is relevant, useful and understandable. In other words, feedback from users is essential. In the section below, the concept of user-centered development is presented.

User centered development

Some of the currently used devices in the medical area were not designed with focus on the final user.[7, 10, 46, 57, 58] Such devices are often not intuitive and have a low usability.[46, 59-61]

To create intuitive and usable displays, an iterative development cycle with user participation can be used.[62, 63] Intuitive displays react in the way users expect it by showing anticipated content, [53, 63-66] and the information reflects the users' needs and tasks.[66, 67] Intuitive and usable devices can be used with very little training.[53] Correct identification of displayed information, low error rates and rapid decision-making indicates an intuitive design.[63] User-centered development means active participation of the people who will finally use the product in the planning, design and development of the product.[53] This process minimizes the learning curve and increases later accuracy and efficiency.[62]

Figure 2 shows an approach of user centered design which follows an iterative approach (ISO 9241-210[62]) with stages a) to f). In stage a) "Plan the human centered activity" the focus of the project is defined and the development is planned. In b) "Requirements gathering" the context of use and future users are determined. In c) "Requirements specification" user specific requirements and organizational requirements are identified. In d) "Develop design solution" a prototype is developed. In e) "Evaluate" user based assessment is carried out. In case the prototype does not satisfy the evaluation, the process is reiterated. Iterations can specify further context of use, user and system requirements and reiterate the design solution. This process is continued until the design solution

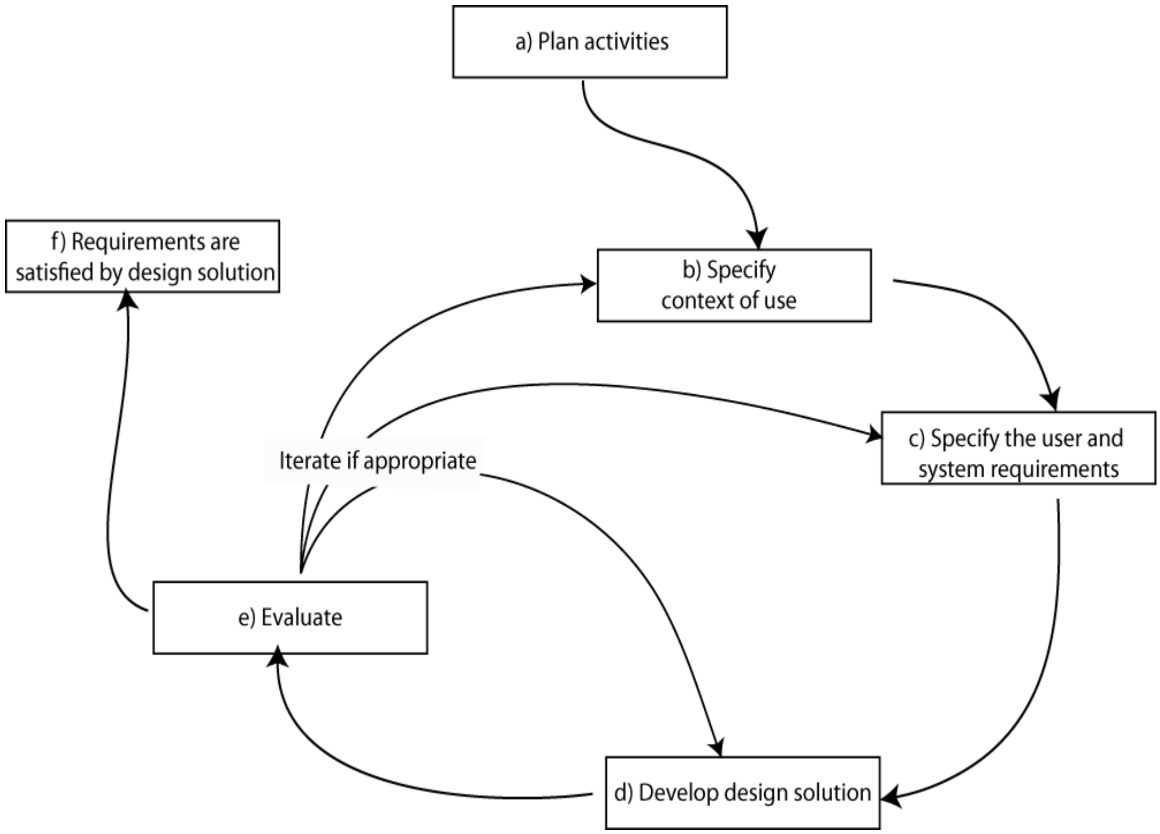

Figure 2 A user centered approach to design interactive system stages of ISO 9241-210[62]

satisfies the evaluation.

Potential problems in user centered design include factors, such as the use of non representative users, and failure to address all potential issues. As a result, only partially satisfying solutions are designed, and proliferated display screens might result. If users participating in the design process are not representative for the final users but the design is adapted to their personality, needs, uses, behavior, and experience it might not suit the needs of the final users.[61] If designers do not address all issues and feedback, the final product might not cover all necessary functions. Users might understand which problems they have, but when asked for their preferences not know how to optimally solve these problems – resulting in a design solution which only partially addresses their underlying needs.[61, 68] Proliferated display screens might be the result of the design attitude “since we can do it, why not include it” with systems that require navigation through multiple cluttered screens to understand the big picture.[69]

In addition to user centered development, design guidelines, e.g., human factors design principles, can be followed to improve the final user interface.

Graphical information display for ICU nurses

A systematic review of evaluations of physiological monitoring displays found that the majority of studies showed improvements in response time, accuracy, and decreased mental workload.[70] Studies that have tested novel interfaces with ICU nurses have discovered improved accuracy,[24, 25, 29, 71] enhanced detection of patient changes,[27, 72] shortened response time,[25, 26, 71] and increased user satisfaction.[26, 71, 73] Graphical data representation has been found to be superior to textual interfaces, and the integration of multiple pieces of information into changing graphical shapes improved the user’s performance in specific cases. Such displays were designed to support different nursing tasks: blood gas monitoring, haemodynamic monitoring, pulmonary monitoring, patient monitoring, order management, and patient management.

For blood gas monitoring Doig, Agutter et al. [24, 29] found a significant increase in the accuracy of diagnosing acid base imbalances for all participants using a novel graphic display which applied gestalt principles and that with the display the status of the pH, PaCO2 and HCo3 values could be more effectively communicated.

In nurses hemodynamic monitoring Effken et al. [26] showed that an ecological display using gestalt principles which visualized anatomical causation and constraints compared to a traditional bar graph display did not improve recognition speed nor overall cognitive workload but lead to greater user satisfaction.

In pulmonary monitoring Liu et al.[74] could show that a graphical visualization of ventilator variables based on gestalt principles used by nursing students compared to a traditional representation did not improve the assessment of patient condition but increased detection of changes and made fewer errors.

In patient monitoring Miller et al.[27, 72] found improved detection of patient changes when patient data was ordered by physiological function, on a single sheet of paper or split between four computer screens.

For nurses order management such as creating, activating, modifying and discontinuing medical orders Staggers et al.[71] found that a graphical compared to a textual interface resulted in faster response time, fewer errors, easier learning, and higher user satisfaction.

In pulmonary monitoring, Wachter et al. [75] found that clinical volunteers using a pulmonary metaphor display based on gestalt principles showed a faster detection of and lower workload for obstructed endotracheal tube and intrinsic peep events. Furthermore, fewer unnecessary treatments were given but improvement in diagnostic accuracy was identified. In an observational study[76] ICU nurses were found to look at the display on average 1.31 times per room visit – less than other care takers.

For patient management Ireland et al.[42] developed a summary screen which users found clear, relevant, easy to learn, and simple to use. Their summary screen showed administration data, and cardiovascular, respiratory, fluid, and temperature information. However, no outcome quantitative evaluation could be found.

Evaluation methods of displays

Display evaluations should be guided by a theoretical model, be based on pilot studies and a power analysis, and use realistic and complex scenarios.[70] Participant's performance can be measured in multiple dimensions. Among them are situation awareness or accuracy, performance time, perceived workload, and user satisfaction.[70] These variables are explained in the following.

Situation awareness

To measure situation awareness multiple methods can be used, dependent on the system to be tested and the experimental setting. These methods include: (i) direct system performance, (ii) direct experimental techniques, (iii) verbal protocols, and (iv) subjective measures.[77] The selection of the measurement technique depends on the system tested. [78-80]

(i) Measuring direct system performance focuses on reaction time to sudden change or a dangerous situation, e.g., recover from a disruption, or time to detect abnormality. This technique requires experts' agreement that the measured performance depends mostly on situation awareness. However, if situation awareness is inferred from the actions that individuals choose to take or their behavior the correlation of good actions / behavior and high situation awareness is not always valid.[17]

(ii) Direct experimental techniques compare an individual's perception of the situation to some predefined reality. Measurement tools are real-time probes embedded as questions in conversations during the test,[81] interruptions of the test and questions following the test. One technique is the Situation Awareness Global Assessment Technique (SAGAT) using multiple choice questions.[82, 83] To measure situation awareness of anesthetists, Zhang et al.[20] used a situation awareness questionnaire which was completed every 2.5 minutes while the simulation was paused.

(iii) In verbal protocols, the participant "thinks aloud" or explains the information relied on during the scenario in a scenario replay. This technique could result in biased results as it relies on the correct interpretation and the memory of the participant.

(iv) Subjective measures are self-assessments, expert judgments, peer ratings, and supervisor or instructor ratings during or after the scenario. Subjective measures ask individuals to rate their own or the observed situation awareness of participants.[84] Techniques are self-assessments, expert judgments, peer ratings, and supervisor or instructor ratings during or after the scenario.[77] Although easily administered, self ratings are limited by the information individuals do not know (the "unknown unknowns"), and subjective measures are rather global with less detail than objective measures.

Concluding the above, during the evaluation of the displays we use a direct experimental technique to measure the nurses' awareness. In our evaluation, a direct experimental technique allows comparing an individual's perception of the situation using different kinds of prototypes. The measurement technique we use is Situation Awareness Global Assessment Technique (SAGAT) using multiple choice questions,[82, 83] with the speed of the scenario based on the user's response time to questions.

Performance time

Time measurements are dependent on the study design. Previous physiological monitoring display evaluation studies measured the time to diagnosis,[29-31, 75, 85] time to detect event/change,[12, 20, 30, 86, 87] time to treatment,[25, 30, 31, 75] time to decision,[85, 88] overall procedure times,[89] and time to complete scenario.[90] Experimenter effects occur as an experimenter's expectations may influence the results of his research.[91] Automatic, participant driven, time measurements can control for manual time measurement biases and are used during our evaluation.

Cognitive workload assessment

Common subjective cognitive workload assessment instruments are NASA Task Load Index (TLX) (Appendix F),[92] the Subjective Workload Assessment Technique (SWAT),[93] and the Workload Profile (WP).[94] All three instruments were found to be equally reliable as Rubio et al.[95] found that all have a high convergent validity. The instrument's intrusiveness was found to be comparable during the test. [95] However, NASA TLX seems to be more reliable to the other two instruments as subjects had problems understanding the dimensions of WP, and SWAT requires exhaustive ranking task prior to the experiment.

NASA TLX uses six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration.[92] For each dimension a score from 0 to 100 is obtained using 20 step bipolar scales. A global score can be calculated by combining the single scores with operator defined different weights.

NASA TLX was found to have good reliability and validity.[96] It was found to have a Cronbach's alpha coefficient of more than 0.8, and the correlation coefficient between item score and total score of more than 0.6 except for performance.[96] Therefore we use NASA TLX for the evaluation study.

User interaction satisfaction

To measure user interaction satisfaction, questionnaires such as the Questionnaire For User Interaction Satisfaction (QUIS)[97] can be used.

QUIS version 7.0 part 3[98] allows assessing six dimensions of user satisfaction of the user's overall reaction to a system. Participants are asked six questions using 9 point Likert scales to score their impression utilizing the computer system (Appendix G). Questions ask participants about their impression employing the system (terrible-wonderful, frustrating-satisfying, dull-stimulating, difficult-easy, inadequate power-adequate power, rigid-flexible). The reliability of QUIS was found to be sufficiently high with Cronbach's alpha of 0.94.[99] Therefore we utilize QUIS for our evaluation study.

CHAPTER 3

IDENTIFICATION OF REQUIREMENTS FOR AN INTEGRATED INFORMATION DISPLAY AT THE BEDSIDE

Prior literature (see Background) has not provided sufficient detail regarding which information ICU nurses are currently missing during frequent and safety-relevant tasks, and a vision about how an integrated display at the bedside could best support their tasks. However, such information is essential in designing a useful integrated display.

The aim of this investigation was to identify requirements for an integrated information display. Objectives were a) to identify frequent nursing tasks, combine them in task categories and identify missing information, b) to identify patient safety critical task categories, and c) to define implications and create a vision for an integrated display.

Methods

With Institutional Review Board approval, the study was performed at the Medical ICU of the University of Utah Health Science Center, the Surgical ICU at the George E. Wahlen Department of Veterans Affairs Medical Center Salt Lake City, and the Shock Trauma ICU of Intermountain Medical Center.

The research consists of five components: 1) observations of nursing in practice settings; 2) classification of nurse activity into tasks; 3) identification of missing information for high-frequency tasks; 4) identification of the most patient safety critical task categories, and 5) definition of implications and a vision for an integrated display. Observations, classification, and identification of missing information are described together.

Observation of nursing task frequency and missing information

Observational studies and root-cause analysis have been successful in identifying challenges and safety problems in the ICU.[16] Observations have been determined to be less intrusive and to have fewer interferences with patient care than other approaches e.g., cognitive work analysis.[100, 101] In a project to develop bedside displays for nurses, Miller et al.[41] used cognitive analysis to determine the information used by medical and nursing staff. Wachter et al. [102] used expert consultation and literature review to determine variables used to detect adverse pulmonary events. No report was found for the development of the display of Effken et al.[26]

Participants

Nineteen ICU nurses were observed for two hours each: ten nurses at a Medical ICU of the University of Utah Heath Science Center, five nurses at a Surgical ICU at the George E. Wahlen Department of Veterans Affairs Medical Center Salt Lake City, and four nurses at a Shock Trauma ICU of Intermountain Medical Center. The sample size was based on Holtzblatt et al.[61] which recommended that there be at least four users per job role (ICU). A larger sample size was selected in the Medical ICU to get a general impression of the workflow in the ICU. Nurses were included if they worked longer than two weeks in an ICU and were taking care of critically ill patients who required technical equipment e.g., ventilators or IV pumps. No demographic data was collected. For each observation, the charge nurse was asked to assign the observation team to a suitable nurse.

Procedures

An adapted form of participant observation[103] was used. The team followed nurses into the patient room, to the central nursing station, and into the medication storage room, but not when nurses left the ICU or requested privacy. Nurses were observed, asked to explain their actions and to state their goals during each action, but different from participant observation the observatory team did not perform actions due to liability issues.

Observers did not ask questions in times of very high workload to assure patient safety. The scribe recorded field notes for each action, goals and comments. For example, for medication administration one stated goal was to keep the patient safe, and a comment was that it was hard to identify new medication orders because they looked like previous orders. In case the nurse performed multiple tasks simultaneously, the scribe focused on recording the most obvious task and if possible any additional tasks performed.

Time periods were selected to be mainly in the timeframe between 8am and 12pm, because in this timeframe most errors were found to occur in a previous study.[104]

Team members

The observation team consisted of a biomedical informaticist with a nursing background, an architectural student, a bioengineering student, and two psychology/human factors students. Team members were trained by the biomedical informaticist. Inter-rater reliability was not measured among the team members' observations. Each observation was performed by one observer and one scribe.

Data analysis

Within 24 hours of the observations, the team met again and the scribe read each field note aloud and the observer entered the note into an Excel spreadsheet (Microsoft Corporation, Redmond, WA). The team used cued recall[105] to reconstruct the situation in case of unclear notes.

Nursing task frequency

The classification of nurse activities was based on the observations field notes. Notes were sorted according to common characteristics by the research team through an iterative process of discussion and classification. Once the tasks were sorted they were assigned names by three ICU nurses. One of the observers (SK) placed each task into one of five task higher-level categories: communication, medication management, patient assessment, organization, and direct patient care. Categorical assignments were validated by an ICU nurse manager independently. Task categories were further described in nursing terms by three ICU nurses through discussion and consensus.

Identification of missing information

To identify missing information, field notes were reviewed after organization into task categories. Information that nurses needed but which was not available to complete a task were identified in two ways. First, if a change in location occurred for the purpose of acquiring that information, an information need was recorded. Second, if a nurse was noted as verbally indicating that the information was not available, an information need was also recorded.

Missing information was then assigned to one of the levels of situation awareness by the author using the following criteria. Perceptional challenges were identified when information was difficult to see or not available at the location needed. Comprehension challenges were identified when several pieces of information had to be combined, or nurses were not sure about the accuracy of information. Projection challenges were determined when information was missing to predict future developments.

Identification of patient safety critical task categories

Participants

10 nurses working at a Medical ICU of the University of Utah Heath Science Center, 12 nurses working at a Surgical ICU at the George E. Wahlen Department of Veterans Affairs Medical Center Salt Lake City, and 11 nurses working at a Shock Trauma ICU of Intermountain Medical Center volunteered to

participate. All ICU nurses working in a setting during a particular day shift were invited to participate. Of the participating nurses, 46% worked in ICU settings for more than five years, the others less. Five invited nurses refused and three nurses did not complete the questionnaire correctly – their responses were excluded.

Questionnaire development

The questionnaires included 34 items: 32 questions related to the previously observed tasks and two questions about information needs (see Appendix A). A nurse (SK) selected the 32 tasks as a representative sample from each of the five previously defined task categories: communication, medication management, patient awareness, organization, and direct patient care. Two additional questions addressed information needs while away from the patient: “assessing a critical patient’s vital signs when in another room” and “assessing reasons for patient’s alarms while in another room”.

Questionnaires were created using the methodology described by Waltz et al.[106] Nurses were asked to rate the patient safety relevance of each task on a Likert scale [107] ranging from 1 “not important” to 7 “very important. Furthermore they were asked if they had more or less than five years work experience in ICU settings.

Data analysis

The answers were tabulated and scored using Excel (Microsoft, Redmont), which was then used to calculate median, mean, and standard deviation for each item.

Implications and vision for an integrated display

Devices which support users' goals improve their usability.[61, 65, 108] Therefore an integrated display should be designed to support nurses' goals and different approaches to work. To create an overarching vision, an affinity diagram was used, allowing consolidation of large amounts of consumer data, and to vision system improvements along key dimensions.[61] The affinity diagram minimized the loss of ideas and supported simultaneous brainstorming by team members.

Team members

Two psychology students and one medical informaticist participated in the initial step of constructing the affinity diagram. Seven team members participated in the visioning process: a bioengineer, a nurse educator, a biomedical informaticist with a nursing background, architectural student, bioengineering student, and two psychology/human factors students.

Procedures

An affinity diagram[61] was built using printed field notes and nurses' comments as individual items. The observatory team attached field notes and comments to a wall and sorted them by relatedness, comparable goals, similar tasks and related problems (see Figure 3). The team wrote description notes which summarized related field notes. All seven team members then "walked the wall,"[61] read through the descriptive notes and identified tasks with missing information. Visions of improved information availability, improved communication and other functions of the integrated display were recorded on post-it notes and attached to the affinity diagram. This process was iterative and consensual.

Results

Observation of nursing task frequency and missing information

Nursing task frequency

Forty-six tasks were identified and combined into five categories. Table 1 shows the observed tasks and their frequency. Using this taxonomy, nurses performed on average 23.4 tasks per hour.

Communication tasks were most frequent, and included communicating with other persons, recording notes about the communication and communication with peers through charting and orders.

Missing information

Challenges for nurses' situation awareness were identified for the high frequency nursing task communication, medication management, and patient awareness, as well as for the three levels of situation awareness perception,

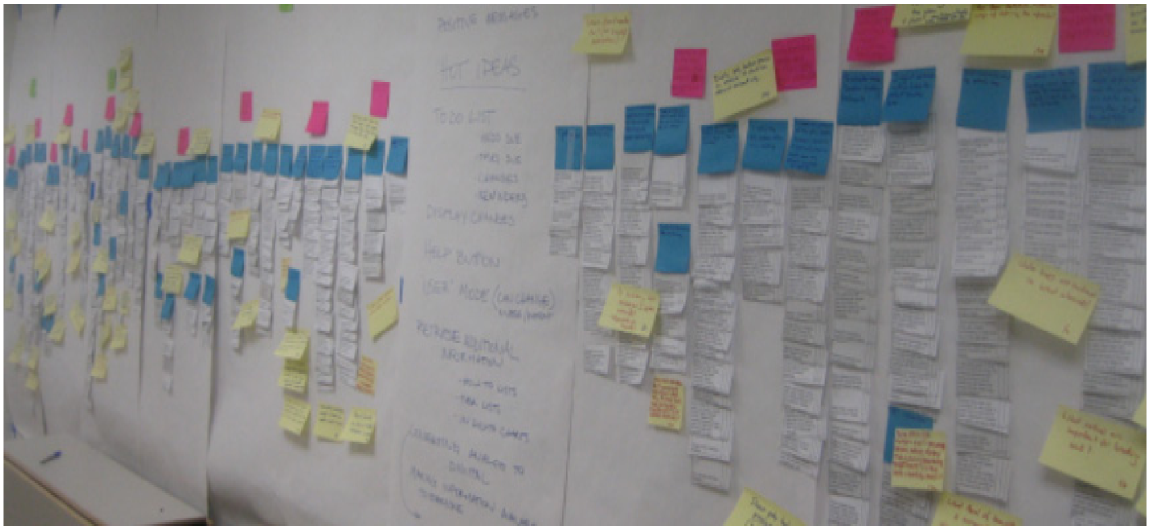

Figure 3 Affinity diagram to identify opportunities for changes in information communication to increase situation awareness

comprehension, and projection.

Communication

During communication tasks nurses spent much time searching and waiting for their communication partners. They either did not know where that person was, when they would be available and at times, they were not even sure if they had the correct individual. Furthermore, they were not sure if other team members were aware of patient changes, and sometimes forgot to communicate (chart) vital signs.

Medication management

During medication management, orders and updates were not available at the bedside (in some ICUs), and not readable from the doorway due to small font sizes. Furthermore, nurses were gathering much information from many different

Table 1 Task frequency and categories of nursing work based on 38 hours of observations in 19 nurses

Category of nursing work	Task	Tasks/ hr
Communication	chart	1.7
	talk to the patient	1.0
	check/sign orders	0.9
	talk with relatives	0.9
	communicate with a physician	0.8
	relay information to another nurse	0.8
	communicate with another nurse to organize workflow	0.6
	ask another nurse for advice	0.5
	communicate with respiratory therapist	0.4
	participate in rounds	0.3
	communicate with unit clerk	0.2
	socialize with another nurse	0.2
	call pharmacy	0.2
	record nursing note	0.1
	Total	**8.6**
Medication management	check medication order/sign order	1.6
	administer medication	1.6
	assess currently administered IV medication	1.5
	acquire medication	0.8
	check medication compatibility	0.2
	record nursing note	0.1
	Total	**5.7**
Patient awareness	patient assessment	1.1
	nurses rounding (at a glance assessments)	1.1
	assess reason for alarm	1.0
	measure urine output	0.6
	record nursing note	0.7
	wound care	0.2
	draw arterial blood sample	0.2
	assess patient's mental orientation	0.2
	assess restraints	0.1
	perform spontaneous breathing trial	0.03
	assessing endotracheal tube position	0.03
	Total	**5.3**

Table 1 continued

Category of nursing work	Task	Tasks/ hr
Organization tasks	set up equipment (IV pump, ventilator…)	1.4
	check equipment	0.5
	await pending task, e.g., admission	0.2
	Total	**2.0**
Direct patient care	support patient in activities of daily life (e.g., eating, drinking, toileting…)	1.2
	suction patient's airways	0.4
	bath	0.1
	perform oral care	0.1
	administer tube feeding	0.1
	pull catheter	0.03
	extubate	0.03
	Total	**1.9**

locations (see Figure 4).

Figure 4 shows an example of information sources used and ways walked during medication administration. A nurse who is in the patient’s room (1) decides to check if new medication needs to be given. On the electronic medical record a new medication is scheduled (2), so the nurse gets the medication from the medication storage room (3). To check if the new medication can run through the same line as one of the current medication, the nurse remembers the current medication (4), and checks the IV compatibility (5a). Furthermore, the nurse checks if the new medication might cause adverse effects which need to be monitored (5b), administers the medication (if compatible) and checks the patients vital signs on the monitor(6).

Patient awareness

During patient awareness tasks, nurses were not notified of alarms and changes in equipment settings. Furthermore, novice nurses were sometimes unsure about assessment procedures in infrequent illnesses, alarming devices and the severity of the alarms.

Situation awareness levels

Table 2 to Table 4 show details on missing information for each situation awareness level. Across all categories perceptional challenges were due to unavailable information or information which was hard to discriminate (Table 2).

Challenges for nurses’ comprehension were largely a result of the need to

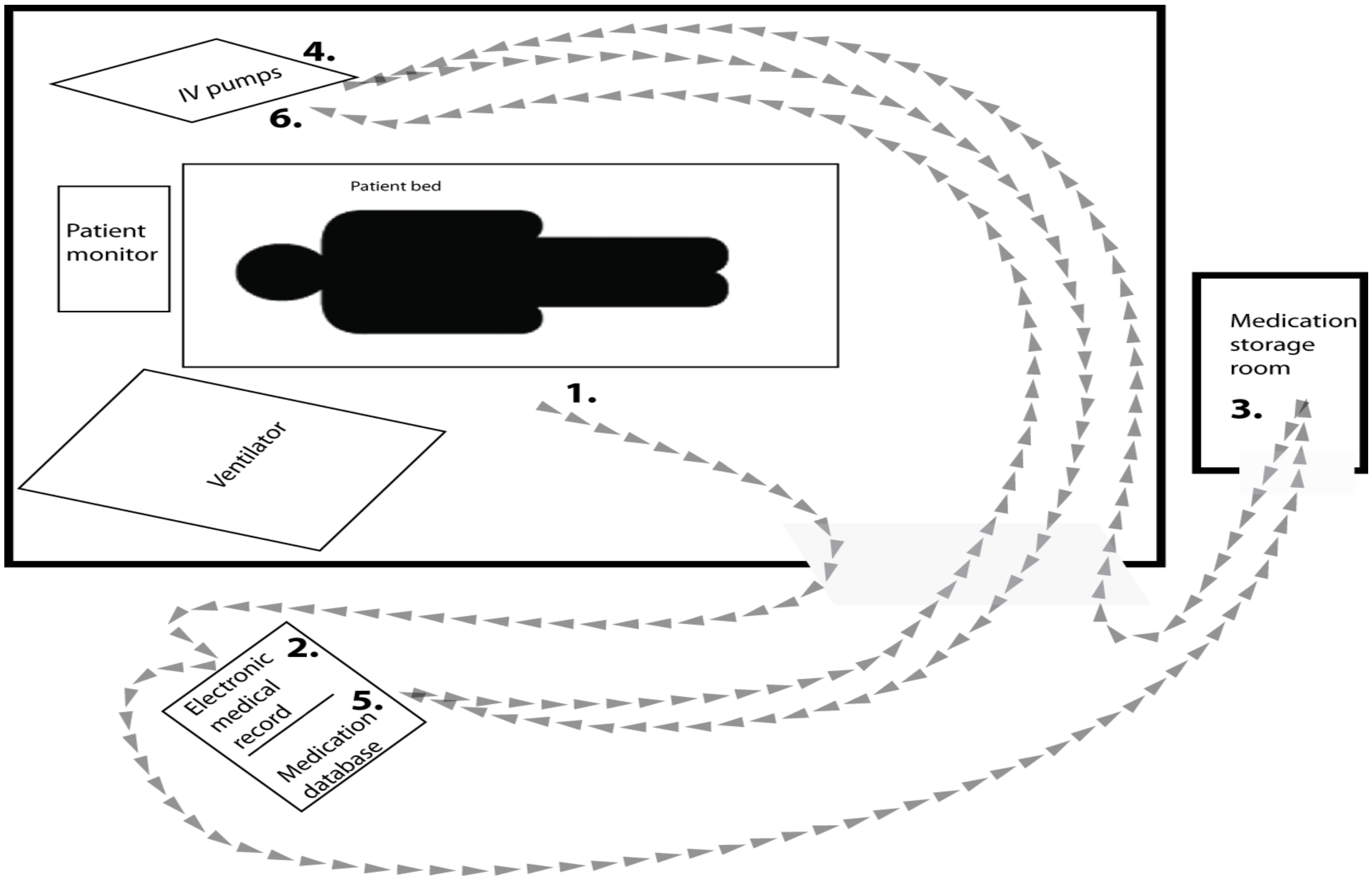

Figure 4 Example of information sources used and ways walked during medication administration. See text for further explanation. [Human Factors and Ergonomics Society 54th Annual Meeting, San Francisco, 2010. "Integrated Information Displays for ICU Nurses: "Field Observations, Display Design, and Display Evaluation", S. H. Koch, N. Staggers, C. Weir, J. Agutter, D. Liu, D. R. Westenskow. Submission ID: 429 Reprinted with permission of the Human Factors Society.]

combine multiple pieces of information from different locations, inaccurate or unclear information, or correct performance of procedures was unknown (Table 3). Challenges for nurses' projection were mainly based on either missing or inaccurate information needed to predict future developments (Table 4).

Identification of patient safety critical task categories

The average patient safety score was 6.0 on a Likert scale ranging from 1 "not important" to 7 "very important, and bathing had the lowest score (4.8). The most patient safety critical category of nursing work were medication management, followed by patient awareness, communication, organization tasks, and direct patient care.

Table 5 shows that although tasks within a category overlapped, most safety critical tasks were associated with medication management (mean = 1.5) and awareness of the patient's status (mean = 2.0). Other critical tasks identified were assessment of the patient's ventilation status and the patient's vital sign trends over time.

Implications and vision for an integrated display

Communication

For communication tasks, two improvements were envisioned: Synchronous communication with other providers and the communication of observations to increase shared knowledge (close and far through voice recognition). Visible

Table 2 Perceptual challenges

Task	Missing Information
Communication	Current contact information of relatives
Medication management	Ordered infusion rate and time
	Medication administration protocol
	Delivery status of ordered medication in medication storage room
	Value of last blood sugar measurement
Patient awareness	Waveform label (yellow and green were hard to discriminate)
	Alarming value on monitor (hard to discriminate due to blue background)
	Results of recently drawn lab values, e.g., blood gas
	Vital sign values (font to small to read from doorway)
Organization	Location of equipment

Table 3 Comprehension challenges

Task	Missing Information
Communication	Location of communication partner
	Awareness of patient change by other involved clinicians
	Recently changed alarm and device settings by other clinicians
	Values to chart (values were inside patient’s room, EMR outside)
Medication management	Changes in current medication orders
	Was unsigned medication administered by previous shift?
	In-line compatibility of new and currently administered medication
	Specific administration instructions for new medication
	Maximum IV infusion rate (catch up with delayed drug delivery)
Patient awareness	Assessment needs for patients with infrequent illnesses
	Alarming device and severity of alarm
	Patient’s mental and physical state
	Condition of patient and alarms while at another location
	Patient development over the last hours
Organization	Utensils needed to prepare for procedure
	Monitor setup or adjustment of settings
	Reason device malfunctioned
	Accuracy of displayed values (measurement errors?)
Direct patient care	Needs of intubated patient
	Protocol to performance of specific (rare) tasks
	Patients comfort level

Table 4 Projection challenges

Task	Missing Information
Communication	Future availability of communication partner
Medication management	Scheduled medication orders which are due Possible adverse effects due to currently administered medication Remaining time of currently infusing medication (medication labels and IV pump font size to small to read from doorway)
Patient awareness	Future development of patient
Organization	Time when rounds, procedures, or consultations on nurses patient will start Time of arrival of new patient
Direct patient care	Future availability of another nurse / nursing assistant for help

delivery status for asynchronous messages, such as pages or voice mails, could allow nurses to be aware if the recipient was aware of the message and allow to prioritize further requests (far).

Medication management

To improve medication management three ideas were created. Changed orders or new orders could be automatically visible to nurses to eliminate frequent login and wrong medication administration (far). Automatic display of medication IV compatibility during medication administration and adverse effects of current medication could allow safer medication management (close). Nurses should see the medication name, delivery rate and time until empty from the doorway (far).

Table 5 Patient safety relevance of tasks ordered by task category on a Likert scale from 1...7 (1 is most relevant 7 is least relevant)

Tasks ordered by category of nursing work	Median	Mean	Standard deviation
Medication management			
Monitoring Medication	1	1.4	0.9
Double checking medication (right order, right medication)	1	1.4	0.8
Administering medications	1	1.4	0.8
Preparing medications	1	1.6	1.1
Total	**1**	**1.5**	**0.9**
Patient awareness			
Knowing reasons for alarms of my patient when outside the patient's room	1	1.4	1.0
Monitoring vitals	1	1.5	0.7
Assessing reasons for alarms	1	1.6	1.0
Monitoring patients Sp02	1	1.7	1.1
Ventilator check	1	1.7	1.0
Monitoring patients trends (over 24 hours)	1	1.8	1.1
Patient assessment	1	1.8	1.1
Monitoring correct position of ventilation tube	2	1.8	0.9
Knowing a critical patient's vital signs when outside of the room	2	1.8	0.8
Monitoring urine output	2	2.0	1.4
Monitoring wound status	2	2.0	1.3
At a glance assessments	2	2.2	1.1
Breathing trial	2	2.3	1.3
Keeping notes of vital signs or tasks that need to be done	2	2.4	1.2
Total	**1**	**1.9**	**1.1**
Communication			
Communication with doctor about patient	1	1.6	0.9
Communication with doctors about orders	1	1.6	1.2
Communication with other nurses about patient	2	1.9	1.2
Communication between nurse and RT about patient	2	1.9	1.2
Communication with patients	2	2.0	1.2
Rounds	2	2.0	1.2
Communication with pharmacy	2	2.0	1.2
Charting	2	2.6	1.7
Communication with patient's family	2	2.8	1.7
Total	**2**	**2.0**	**1.3**
Direct patient care			
Suctioning	1	1.7	1.2

Table 5 continued

Tasks ordered by category of nursing work	**Median**	**Mean**	**Standard deviation**
Drawing blood	2	2.2	1.5
Oral care	2	2.2	1.4
Feeding	2	2.3	1.4
Bathing	3	3.2	1.5
Total	**2**	**2.4**	**1.5**
Organization tasks			
Communication to organize procedure	2	2.0	1.0
Setting up equipment	2	2.4	1.2
Total	**2**	**2.2**	**1.1**

Patient awareness

For patient management the following changes to information communication were imagined: The patient's vital signs should be easily distinguishable from the doorway to support nurses' rounding (far). Alarms in the nurses' second patient should be automatically shown at the nurses' present location (far). Direct review of the patient's past vital signs in combination with past drug delivery could allow easier titration of medications to desired effect (close).

Organization

To improve organization tasks, the detection of errors in equipment could be supported by visual step-by-step instructions- comparable to error detection support in Xerox machines (close).

Direct patient care

For direct patient care, the vision was to provide a list of tools needed to perform and step-by-step procedure instructions to guide inexperienced nurses through infrequent procedures.

Discussion

Medication management received the highest rating in terms of patient safety concerns and the second highest rating in terms of frequent tasks. Therefore, it is particularly important issue. Communication and awareness of the patient were performed with high frequency. Information deficits were identified in all three levels of situation awareness. Nurses' perception, comprehension, and projection of changes in patient and treatment were challenged due to distance of related information, lack of visible treatment change communication, and information which was laborious to retrieve.

Displays should therefore primarily support medication management and additionally improve communication and patient awareness, and should focus on all three levels of situation awareness. Support should include automatic change notification, close display of related information, context sensitive decision support, improved awareness of changes in nurse's second patient, and implications for future work for the nurse.

CHAPTER 4

DEVELOPMENT AND FINE TUNING OF AN

INTEGRATED INFORMATION DISPLAY

The previous chapter found that medication management, awareness of the patient's state, communication, and identification of problems in the nurse's second patient needed most attention when designing an information display for the bedside. This chapter defined a vision for an integrated display, and the proactive and reactive approaches of nurses' work which should be considered when designing an integrated display.

This chapter aimed to develop an intuitive integrated information display with useful information content for nurses. Figure 5 shows that the development process consisted of two major steps: rough prototypes identifying design concepts (Figure 5b) and refinement of intuitiveness and accuracy (Figure 5c).

Rough prototypes

The initial step with roughly designed prototypes had three iterations of prototype designs. Users were engaged at strategic points which allowed the developers to receive focused feedback on the specific prototypes.

Overall goals

Intuitiveness and later adoption increases with compatibility of the device with the user's past experiences.[109] Therefore the aims of the rough prototype iterations were to probe for and improve information organization and information content for an integrated information display at the bedside.

Figure 5 Overview of the integrated display development. Identification of information need, iterative display design, and evaluation compared to existing devices.
[Human Factors and Ergonomics Society 54th Annual Meeting, San Francisco, 2010. "Integrated Information Displays for ICU Nurses: "Field Observations, Display Design, and Display Evaluation", S. H. Koch, N. Staggers, C. Weir, J. Agutter, D. Liu, D. R. Westenskow. Submission ID: 429 Reprinted with permission of the HF Society.]

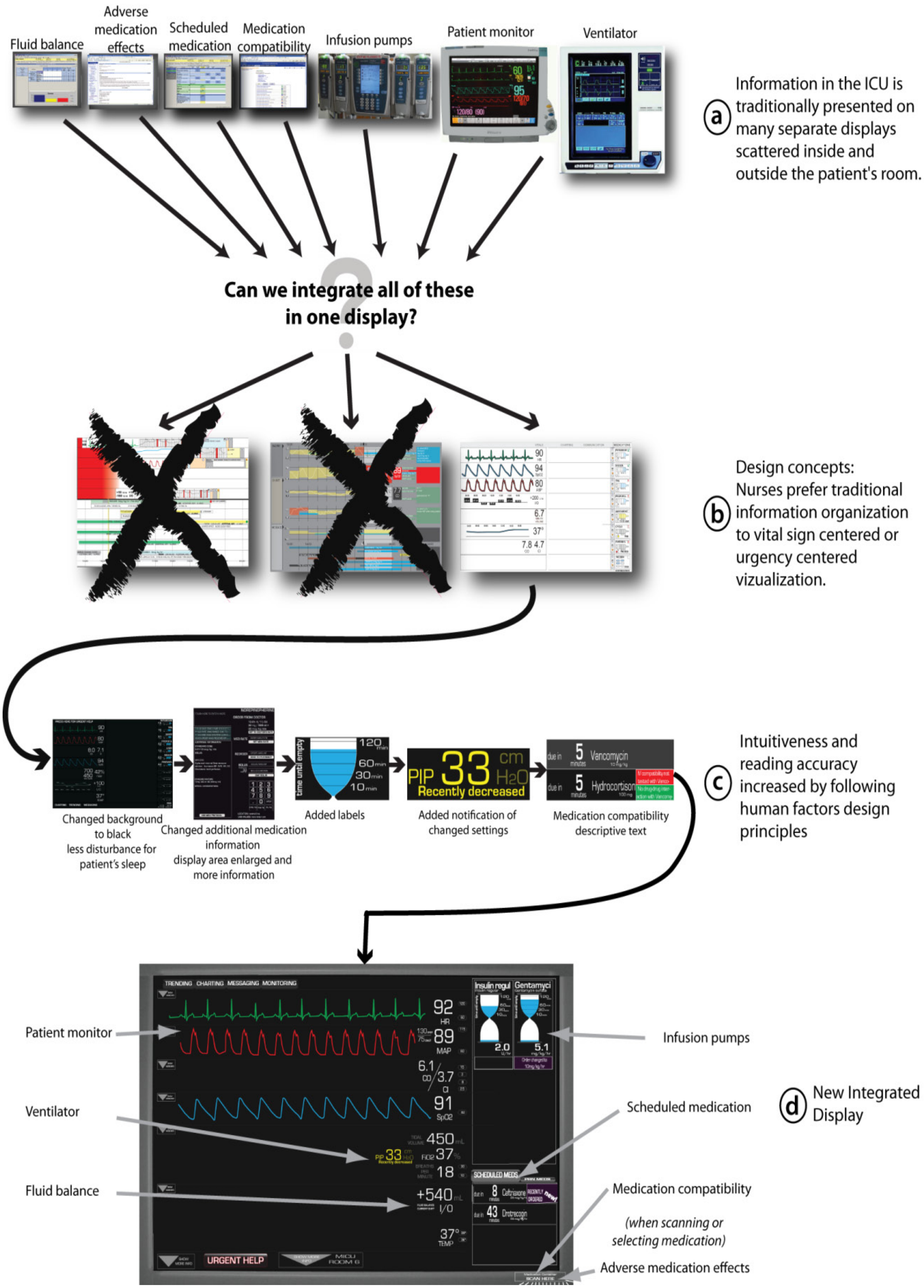
Fluid balance
Adverse medication effects
Scheduled medication
Medication compatibility
Infusion pumps
Patient monitor
Ventilator
a
Information in the ICU is traditionally presented on many separate displays scattered inside and outside the patient's room.
Can we integrate all of these in one display?
b
Design concepts:
Nurses prefer traditional information organization to vital sign centered or urgency centered vizualization.
Changed background to black
less disturbance for patient's sleep
Changed additional medication information
display area enlarged and more information
Added labels
Added notification of changed settings
Medication compatibility descriptive text
c
Intuitiveness and reading accuracy increased by following human factors design principles
Patient monitor
Ventilator
Fluid balance
Infusion pumps
Scheduled medication
Medication compatibility
(when scanning or selecting medication)
Adverse medication effects
d
New Integrated Display
URGENT HELP

Figure 6 shows the goals of the three iterations of rough prototyping. The first prototype iteration tried to identify nurse's preferences on overall information organization. The second design iteration aimed to identify preferences on information visualization. The third iteration focused on identifying information content nurses wanted to see on display elements and information they expected when interacting with the display at different types of ICU's.

Overall methods

Prototyping results in products which better meet users' expectations and needs.[61, 110] Paper prototyping suits early stages of design and lets the designer refine the user requirements, functionality, and the information architecture, e.g. based on interviews with the final user.[110]

Instrumentation

Setting

With Institutional Review Board approval, the study was performed at the Medical-, Surgical-, and Burn Trauma ICU as well as the Neurological Critical Care of the University of Utah Heath Science Center. Interviews were conducted in the ICU break rooms between 9:00pm and 12.30am.

Instruments

Prototypes were designed to provide information for medication management, awareness of the patient's state, and communication. The

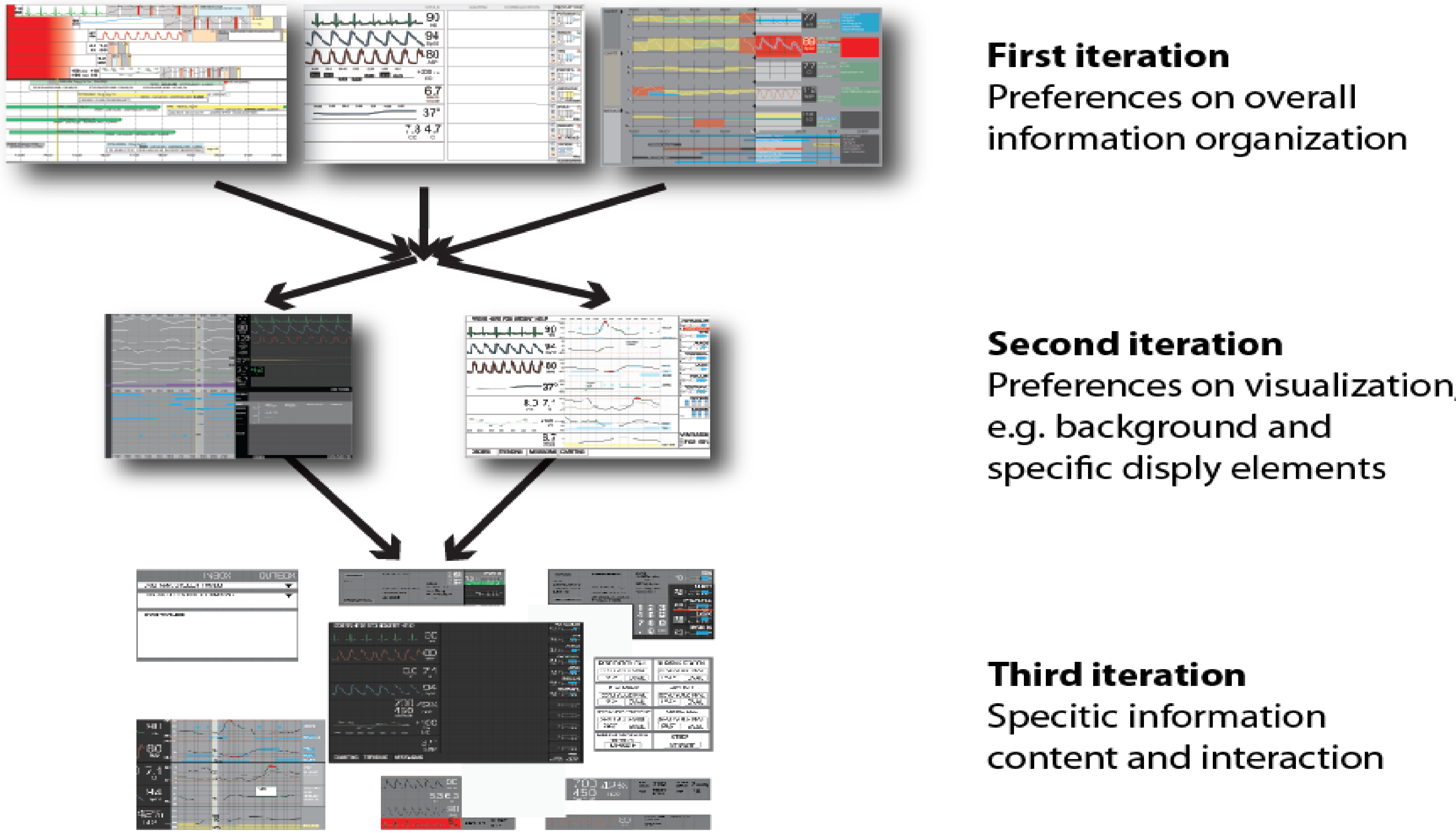

Figure 6: Goals of the rough prototyping and prototypes used. The first iteration aimed to identify nurses preferred information organization. The second iteration compared different visualizations, and the third iteration focused on specific information content and interaction preferences

previously defined implications and vision for an integrated display (see previous Chapter) guided rough information content, and information hierarchy of close and far views. Information which had to be visible from afar was mainly related to patient awareness and awareness of current medication. Information visible from nearby was often related to medication management. Rough prototypes were sketched on a computer, printed, and discussed with individual nurses.

The instruments used to collect this high level information were general in nature (interviews, discussions) as were the graphic examples of the displays. As the iterations became more and more refined, the instruments to gather data were adapted to the stage of refinement. Different questions were pertinent at different stages dependent on the aim of the iteration.

Procedures

Nurses currently working at ICUs were invited to participate in the interviews by the interviewers. Interviews were conducted one-on-one and were administered to different nurses simultaneously by two interviewers: an information-architect, and a medical informatician / nurse. Interviews consisted of a) introduction – the goals of the study and the prototype(s), b) interview - questions dependent on the goals of the interviews, and c) wrap up –nurses were thanked. Interviews were structured according to a list of display elements which was used to guide the sequence of questions. Nurses were asked open-ended questions[59] about their understanding and opinion of each display element, and could expand upon details of their interest. The answers and opinions were recorded on printed spread sheets organized by display element and prototype.

First iteration

The first iteration aimed to identify nurses' preferences on information organization.

Methods

Participants

Four nurses working at the Medical ICU, three female and one male, participated in the first round of prototype interviews. Their average age was 32 years (standard deviation SD 8.9), their daily computer use was 5.6 hrs (SD 4.3), and their years working at ICU settings were 4.1 (SD 2.7).

Procedures

In the first iteration, the prototypes with different information organization were explained to nurses and nurses were asked to select their preferred prototype: "Which of the prototypes do you like most for your daily work?"

Prototypes

Figure 7 shows the three prototypes were designed based on nurses' proactive and reactive approaches to work (see previous Chapter). The prototype shown in Figure 7a focused on support for proactive work approaches, the one in Figure 7b concentrated on reactive work attitudes. The prototype in Figure 7c.

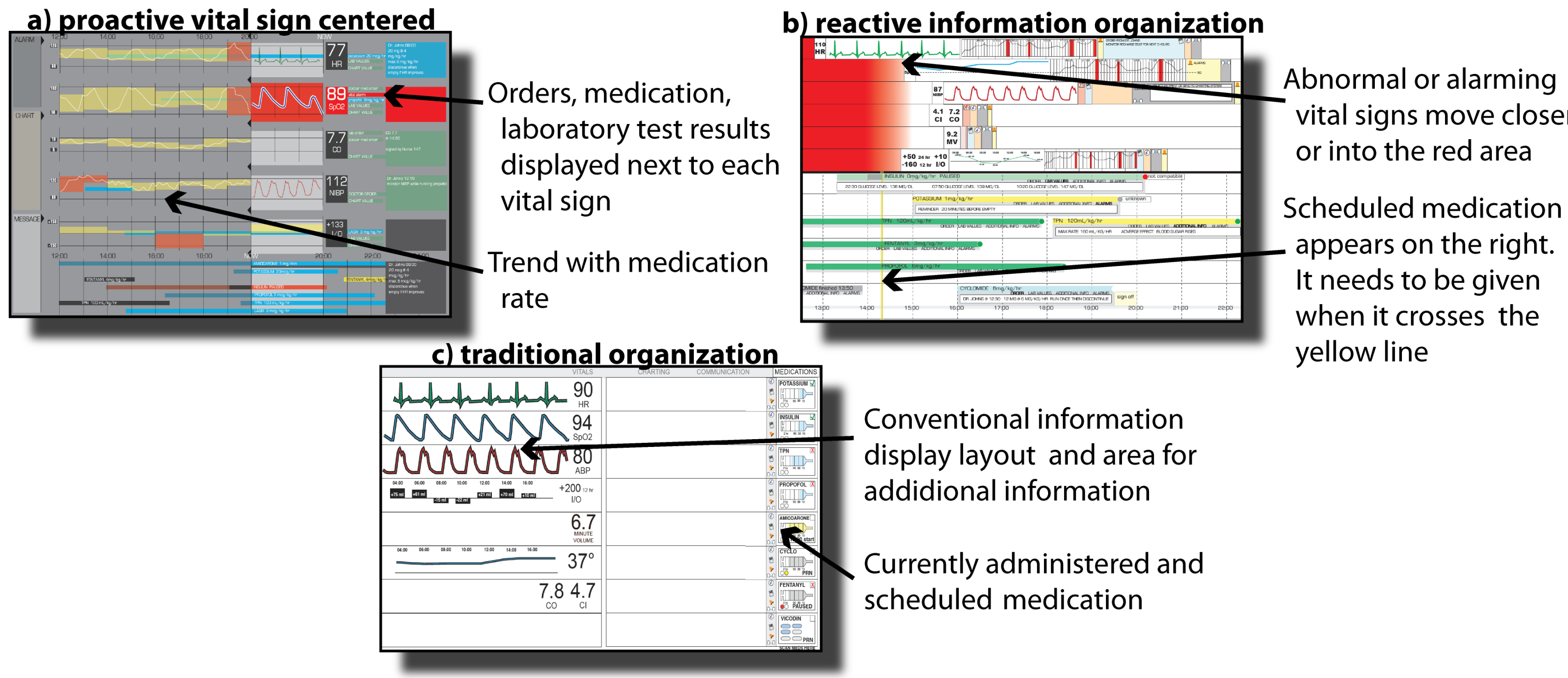

Figure 7 First iteration - Prototypes to identify overall information organization preferences based on nurses' approach of working.
a) proactive vital sign centered - orders, laboratory test results and medication are shown next to the vital sign which they might influence. It allowed nurses to continuously monitor the patient trend and the influence of medication over time, and to predict future actions. b) reactive information organization – nurses are notified about urgent tasks and values they should notice. Values were abnormal vital signs and scheduled medications which both moved gradually to the left side to the red area depending on the amount of attention needed and deviation. c) traditional organization – a close resemblance to known patient-monitoring displays with syringes that show the medications being delivered and scheduled.

tried to satisfy both approaches simultaneously in a traditional information organization.

The prototype in Figure 7a supported proactive work and shows orders, laboratory test results and medication next to the vital sign which they might influence. It allowed nurses to continuously monitor the patient trend and the influence of medication over time, and to predict future actions.

Figure 7b shows a prototype to support reactive work by notifying nurses of urgent tasks and values they should we aware of. Values were abnormal vital signs and scheduled medications which both moved gradually to the left side to the red area depending on the amount of attention needed and deviation.

Figure 7c shows the prototype to support both proactive and reactive approaches by enhancing a traditional patient monitor. It has a close resemblance to known patient-monitoring displays, with additional syringes showing the medications being delivered. Proactive nurses can drill down by exploring additional information available upon request and predict future care plans. Reactive nurses are notified of care steps and abnormal values by countdowns and automatic notifications.

Results

During the first iteration, three of four nurses preferred the enhanced conventional information organization display (Figure 7c). They indicated that it resembled their current patient monitors, had easy-to-see current and scheduled medications, and looked uncluttered

Second Iteration

The second design iteration aimed to identify preferences on information visualization.

Methods

Participants

Five female nurses working as the Medical ICU participated in the second round of prototype interviews. Their average age was 32.3 years (standard deviation SD 1.5), their daily computer use was 5.1 hrs (SD 4.8), and their years working at ICU settings were 5.6 (SD 6.2).

Procedures

In the second round, participants were asked to select preferred display elements: “Which of these display elements would you prefer for your daily work?”

Prototypes

Figure 8 shows prototypes with different display elements supporting specific nursing tasks. These prototypes focused on examples of information content for medication management, ventilation, communication, and trending.

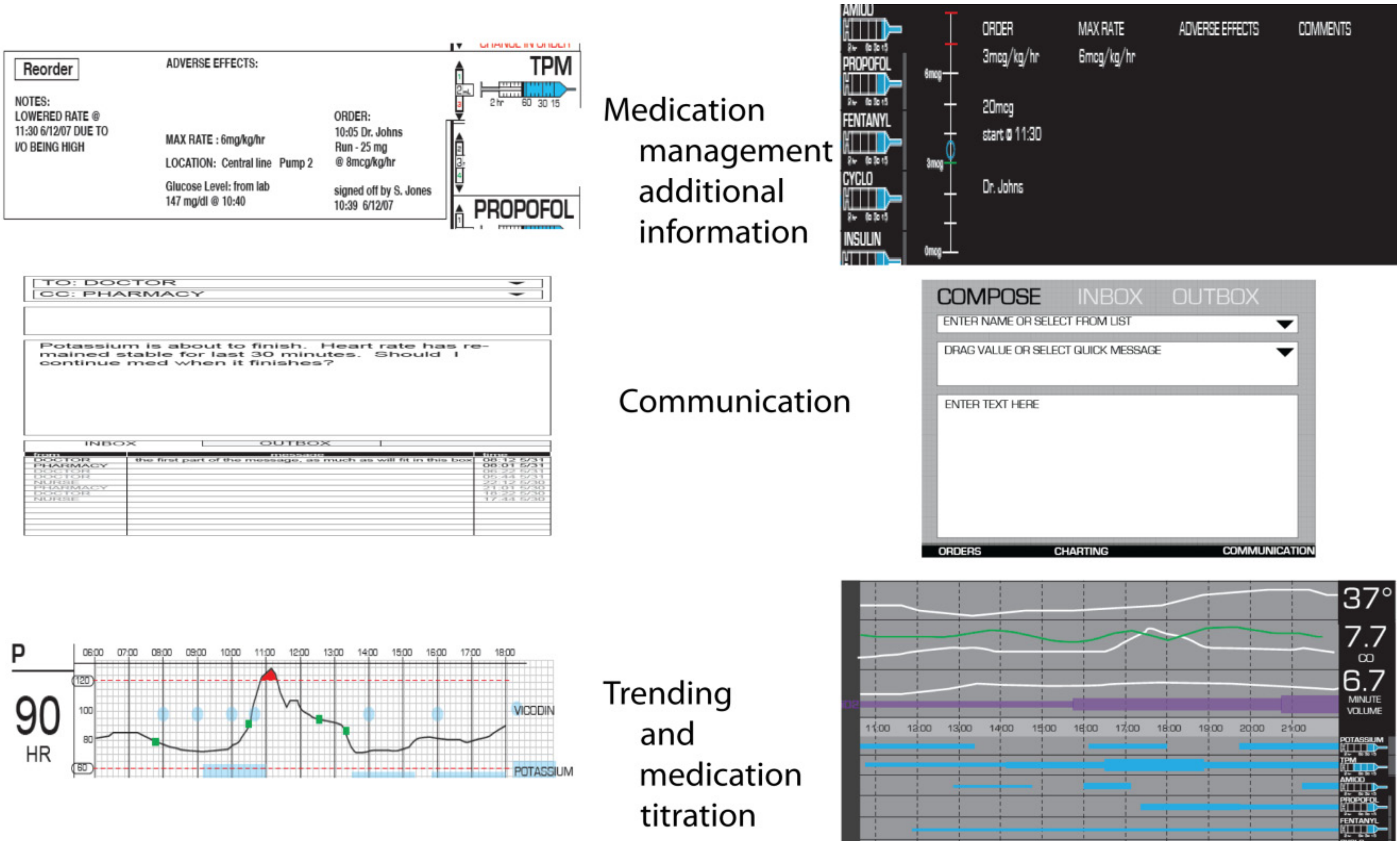

Figure 8 Second iteration - Examples for different information representations for medication management, communication, and trending

Results

In the second iteration, four of five suggested adding medication trends directly alongside vital sign trends. Some nurses complained that the exact values on the trend were hard to identify. The majority selected black as preferred background color, and to constantly see the medication infusion rate on currently active medication infusions.

Third iteration

The third iteration focused on identifying information content nurses wanted to see on display elements and information they expected when interacting with the display. The study was expanded on additional types of ICUs.

Methods

Participants

Sixteen nurses, 12 female and 4 male, participated in the second round of prototype interviews. Five nurses were working at the Burn Trauma ICU, five at the Neurological Critical Care Unit, and six at the Surgical ICU. Their average age was 29.7 years (SD 10.8), their daily computer use was 4.5 hrs (SD 3.2), and their years working at ICU settings were 4.3 (SD 2.7).

Procedures

In the third round, nurses were asked about their understanding of display elements, possible interaction and suggested information content. Interviewers pointed on each display element and asked nurses what they expected to see when pressing the element on the main screen. Then the pop-up screen for the element was shown and nurses were asked if the information was sufficient, or if they would add or remove something. Questions were: "What do you think this is?", "What do you expect to happen if you touch this?", and "Is the information shown sufficient for task X - or which information would you want to add or remove?"

Prototypes

Figure 9 shows a prototype designed using the results of the prior interviews to ask nurses for suggestions and possible interaction with the prototype. Pop-up screens were used in the empty central area to give information to support medication management, trending, charting, and communication tasks.

Results

Table 6 shows information content nurses suggested for display elements and when interacting with them. Nurses demanded that the level of details on each element should be adaptable to individual nurses' monitoring preferences and to the patient's condition. To increase accuracy, nurses decided that infusion rate and alarm settings should be changed using buttons instead of sliders.

When asked about the function and meaning of display elements, some nurses were not immediately able to identify intended function and shown values of some elements.

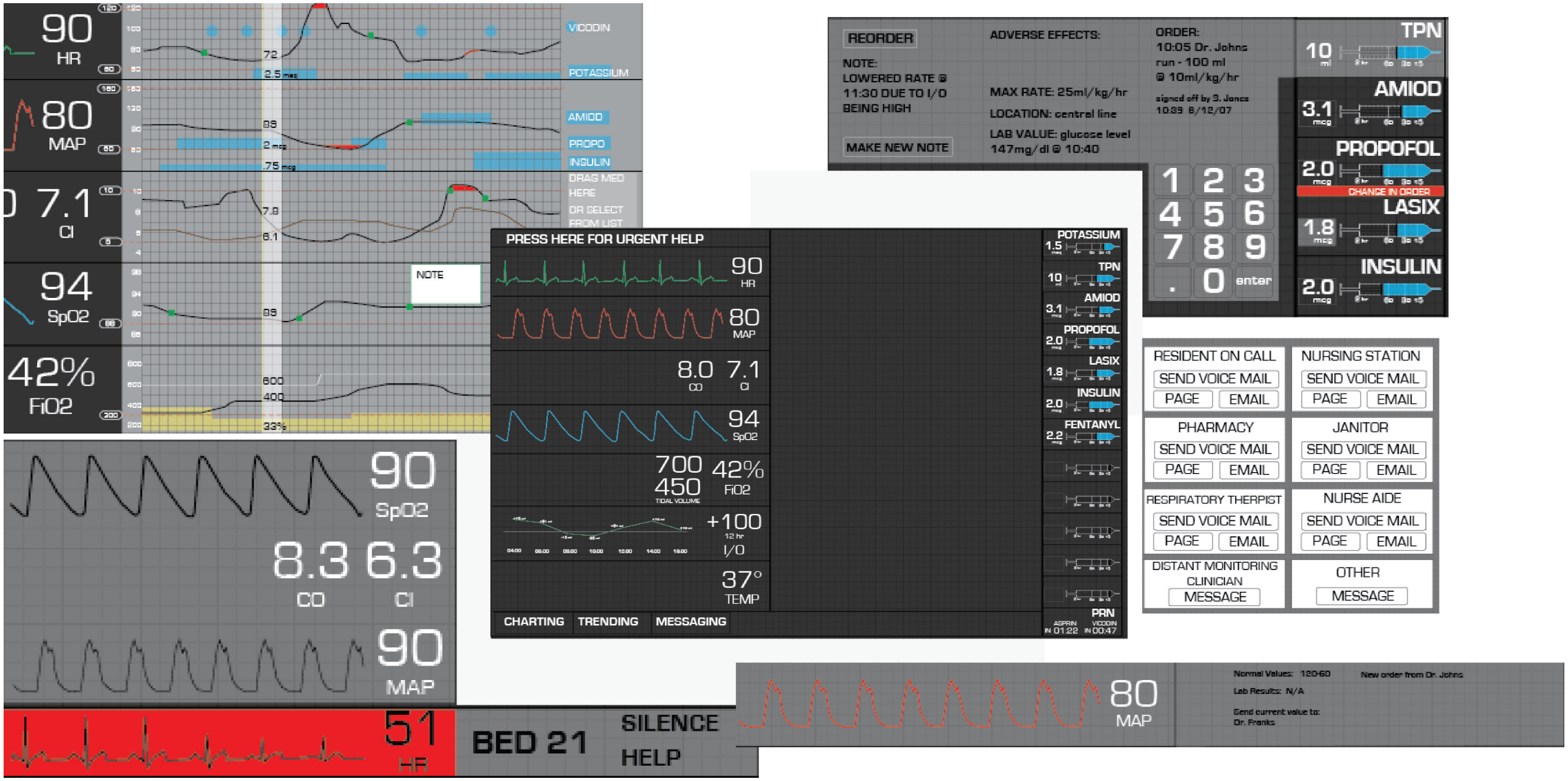

Figure 9 Third iteration – Third prototype surrounded by popup screens which show possible information content upon interaction. Popup screens of supported tasks are displayed in the central black area and discussed with nurses. The figure shows in the top right corner the screen for medication assessments, and clockwise direct communication, display settings, alarm in the second patient, and trending

Table 6 Frequently suggested information content per display element

Display element	Expected or suggested information content
Trending	Past alarms Value alarming variable, alarm duration Waveform at a specific time Charting of specific events on the trend
Patient awareness (while in the room)	Change alarm settings, scale waveform, zero ECG or blood pressure transducer Automatic detection of artifact in vital signs Normal waveform for comparison Influencing factors, e.g., medication, paced patient
Patient awareness (while away in the other patient's room)	Kind and severity of alarm Current vital signs Silence alarm or relay to coworker to silence alarm *Optionally:* Trend
Medication administration	IV compatibility with current medication Doctor's order Concentration of active ingredient Select/change infusion rate and administer bolus
Medication assessment	Adverse side effects Time started, last time given Maximum infusion rate dependent on pat. metabolism Associated laboratory test results
Charting	Tab with access to current charting system Automatic charting of displayed values with confirmation Fast charting of specific values, e.g., urine output
Communication	Leave message for next nurse working with patient Notification of changes in orders without interaction Contact coworker by function, e.g., respiratory therapist

Discussion and implications

The interviews allowed identifying nurses' preferences on information organization and information content. However, some nurses could not intuitively identify the function or shown values of some display elements. Therefore, the intuitiveness and usefulness of the display might be improved through more formal evaluation and improvements.

Refined prototypes

The second development step had four display iterations which were refined based on nurses' feedback.

Overall goals

The aim of this development phase was to improve intuitiveness of display elements and reading accuracy of values shown by these elements. Overall, we aimed to increase both measures to an average of 95% correct answers and to archive a high perceived usability for the final prototype design iteration.

Overall methods

Questionnaires can be used to solicit detailed feedback from larger user groups, and to expose all respondents to uniform stimuli.[106, 111] Questionnaires were developed which showed essential elements and details of the display.

Setting

With Institutional Review Board approval, the study was performed at the Medical-, Surgical-, and Burn Trauma ICU as well as the Neurological Critical Care of the University of Utah Heath Science Center.

Instruments

A nine page questionnaire measured intuitiveness and correct extraction of display information and collected comments. A cover letter asked nurses to complete the questionnaire alone without help from others and introduced them to the purpose of the display. Questionnaires were created using InDesign (Adobe, San Jose, CA), and were designed according to a multiple choice guideline[112] to have the question text in the multiple choice stem and short answer options.

We operationalized intuitiveness as the rate of correct identification of display elements, and usability as the rate of correct information extraction. Thirty-four multiple choice questions probed intuitiveness for depicted display elements, or correct extraction of the depicted information (see Appendix B). Twenty questions asked nurses to name display elements. Fourteen questions asked nurses to retrieve values shown by the display elements. First, nurses named display elements of the prototype's main screen. Then nurses identified details about the display elements and elements on additional display screens. The questionnaires showed different states of the patient and treatment, e.g., a vital sign trend which showed the influence of a medication, a new order, current medication which was nearly empty, or IV incompatible medication. Appendix B reports the questions used.

Usability was measured for the last prototype design iteration and included in the last questionnaire. Nurses were asked for the eight main display elements on a 7-point Likert scale. "I prefer this presentation of information over the presentation I currently use" (strongly disagree, disagree, somewhat disagree, neither agree nor disagree, somewhat agree, agree, strongly agree).

Procedures

Questionnaires were distributed to the charge nurses in each ICU at the beginning of the night shift (around 7pm). The charge nurse distributed the questionnaires and collected completed questionnaires. At 1am, completed questionnaires were collected. Instructions for nurses asked them to complete the questionnaires alone without the help of their colleagues.

Excel (Microsoft, Redmond) was used to calculate the average of correct answers. Each question had the same weight and contributed equally to the result. Nurses' comments were not statistically analyzed but incorporated - if possible - in the next design iteration. Nurses' usability rating (7-point Likert scale) was summarized for agreement.

Fourth iteration

The aim of this evaluation was to identify areas of improvement for recognition and extraction of information. It was performed based on the fourth prototype.

Methods

Seven nurses participated in the first questionnaire. One was working at the Medical ICU, four at the Surgical ICU, and two at the Neurological Critical Care. Their average age was 40.3 years (standard deviation SD 15.1), their daily computer use was 4.5 hrs (SD 4.5), and their years working at ICU settings were 10.8 (SD 12.8).

Results

Table 7 and Table 8 show that deficits existed in the intuitive recognition of current, scheduled, and PRN medication, as well as trending of vital signs and medication and in the correct extraction of information in all elements of the display.

This iteration aimed to measure if improvements of the sixth prototype in specific display areas could improve nurses' recognition and extraction of information in these areas.

Table 7 Fourth iteration - recognized display elements (percentage correct)

	Correctly recognized
Average	86%
Trending	86%
Currently administered medication	76%
Scheduled medication	17%
PRN medication	83%
Additional medication information	100%
Fluid balance	100%

Table 8 Fourth iteration - extracted information (percentage correct)

	Correctly recognized fourth iteration
Average	59%
Trending	62%
Currently administered medication	52%
Scheduled medication	43%
PRN medication	43%
Fluid balance	67%

Fifth iteration

Methods

Sixteen nurses participated in the second questionnaire. One was working at the Medical ICU, five at the Neurological Critical Care, and ten at the Surgical ICU. Their average age was 32.7 years (standard deviation SD 8.3), their daily computer use was 4.3 hrs (SD 4.9), and their years working at ICU settings were 4.9 (SD 5.3).

Results

Table 9 and Table 10 show that major deficits exist regarding correctly identifying display elements and extracting information. As the questions of the fifth iteration did not cover the same elements as in iteration four, the results cannot be compared with the previous iteration.

Sixth iteration

The sixth evaluation step aimed to measure if improvements in specific display areas could increase recognition and extraction of information in these areas based on the sixth prototype.

Methods

Twenty-two nurses participated in the third questionnaire. Five were working at the Medical ICU, seven at the Surgical ICU, five at the Neurological Critical Care, and five at the Burn Trauma ICU. Their average age was 32 years

Table 9 Fifth iteration - recognized display elements (percentage correct)

	Fifth iteration
Average	88%
Trending	88%
Currently administered medication	92%
Scheduled medication	80%
PRN medication	88%
Additional medication information	N/A
Fluid balance	N/A

Table 10 Fifth iteration - extracted information (percentage correct)

	Fifth iteration
Average	76%
Trending	78%
Currently administered medication	90%
Scheduled medication	75%
PRN medication	75%
Fluid balance	100%

(standard deviation SD 10.5), their daily computer use was 3.6 hrs (SD 3.6), and their years working at ICU settings were 6.2 (SD 9.9). Questionnaires covered a selection of display elements. Results can therefore not be compared to the results of the first and last evaluation.

Results

Table 11 and Table 12 show that some deficits exist regarding correctly identifying display elements and major deficits regarding the correct extraction of information. As the questions of the sixth iteration did not cover the same elements as in iteration four and five, the results cannot be compared.

Table 11 Sixth iteration - recognized display elements (percentage correct)

	Sixth iteration
Average	92%
Trending	92%
Currently administered medication	86%
Scheduled medication	71%
PRN medication	77%
Additional medication information	98%
Fluid balance	100%

Table 12 Sixth iteration - extracted information (percentage correct)

	Sixth iteration
Average	86%
Trending	97%
Currently administered medication	61%
Scheduled medication	95%
PRN medication	95%
Fluid balance	100%

Seventh iteration

The overall evaluation step aimed to measure if the improvements of the display overall would result in a recognition and extraction of information of at least 95% and to measure perceived usability when using the seventh iteration.

Methods

Twenty-three nurses participated in the fourth questionnaire. Five were working at the Medical ICU, ten at the Surgical ICU, three at the Neurological Critical Care, and five at the Burn Trauma ICU. Their average age was 34.7 years (standard deviation SD 9.2), their daily computer use was 7.4 hrs (SD 4.4), and their years working at ICU settings were 4.7 (SD 6.4).

Results

Correct recognition

Table 13 and Table 14 show that compared to the fourth iteration the overall percentage of correctly recognized elements reached to 96% and the correctly extracted information was 97%. Compared to the fourth iteration, correctly recognition increased on average by 10% with the largest increase of 83% in the recognition of scheduled medications. The correct extraction increased on average by 38% with the largest increase of 57% in scheduled and PRN medication.

Perceived usability.

Table 15 shows that 86% nurses preferred the integrated display over the displays they currently use in the ICU. Table 16 lists relevant improvements in human factors principles between the fourth and the seventh prototype. Many display elements differ on a smaller scale such as labels and icon shape. Improvements were made in labeling, the inclusion of multiple indicators for similar values, higher saliency of relevant information, and better resemblance of display elements to the depicted values. Figure 10 depicts these changes for the elements used in medication management.

Table 13 Sixth iteration - recognized display elements (percentage correct)

	Seventh iteration
Average	96%
Trending	94%
Currently administered medication	97%
Scheduled medication	100%
PRN medication	87%
Additional medication information	95%
Fluid balance	100%

Table 14 Seventh iteration - extracted information (percentage correct)

	Seventh iteration
Average	97%
Trending	95%
Currently administered medication	100%
Scheduled medication	100%
PRN medication	100%
Fluid balance	100%

Table 15 Usability evaluation of the seventh iteration

	Main screen	Communication	Medication	Additional med. Info	Fluid balance	Trending	Alarm other patient	Ventilator
I prefer this presentation of information over the presentation I currently use. Somewhat – strongly agree	86%	86%	91%	71%	95%	78%	91%	95%

Table 16 Improvements of data presentation in the seventh prototype iteration compared to the fourth iteration and improved human factors principle

Element	Fourth design iteration	Seventh design iteration	Human factors principle
Communication	-Voicemail icon looked like speaking person -Messages were unlabeled icons	-Voicemail icon looked like recorded tape -Messages were labeled icons	-Mental model[54] -Labeling[7]
Medication	-Current, scheduled and PRN medication had same location and comparable icons	-Different location for scheduled and PRN medication and list representation	-Proximity of related information[49, 50]
	-In the current medication, the time until empty looked like fluid level in medication bag	-In current medication, icons were changed to hour glasses	-Pictorial realism[55] -Mental model[54] -Redundant coding[7]
Medication additional information	-Nurses comments indicated the need for medication charting	-Medication charting was added -Elements were rearranged by relatedness	-Proximity of related information[49, 50]
Fluid display	-Intake and output were ordered by source -Balance looked similar to other data elements	-Sources of intake and output were ordered according to positive or negative -Overall balance was separated and printed in bold at the side of table	-Proximity of related information[49, 50] -High saliency[53] -Addressing user characteristics[11, 14, 56]

Table 16 continued

Element	Fourth design iteration	Seventh design iteration	Human factors principle
Trending	-Trending curve scale had small numbers -Medication trend shown as blocks, small scale	-Trending curve scale had larger numbers -Medication trend was shown as small bubbles and enlarged scale -Separating space was added to the trend	-High saliency[53] -Mental model[54] -Labeling[7]

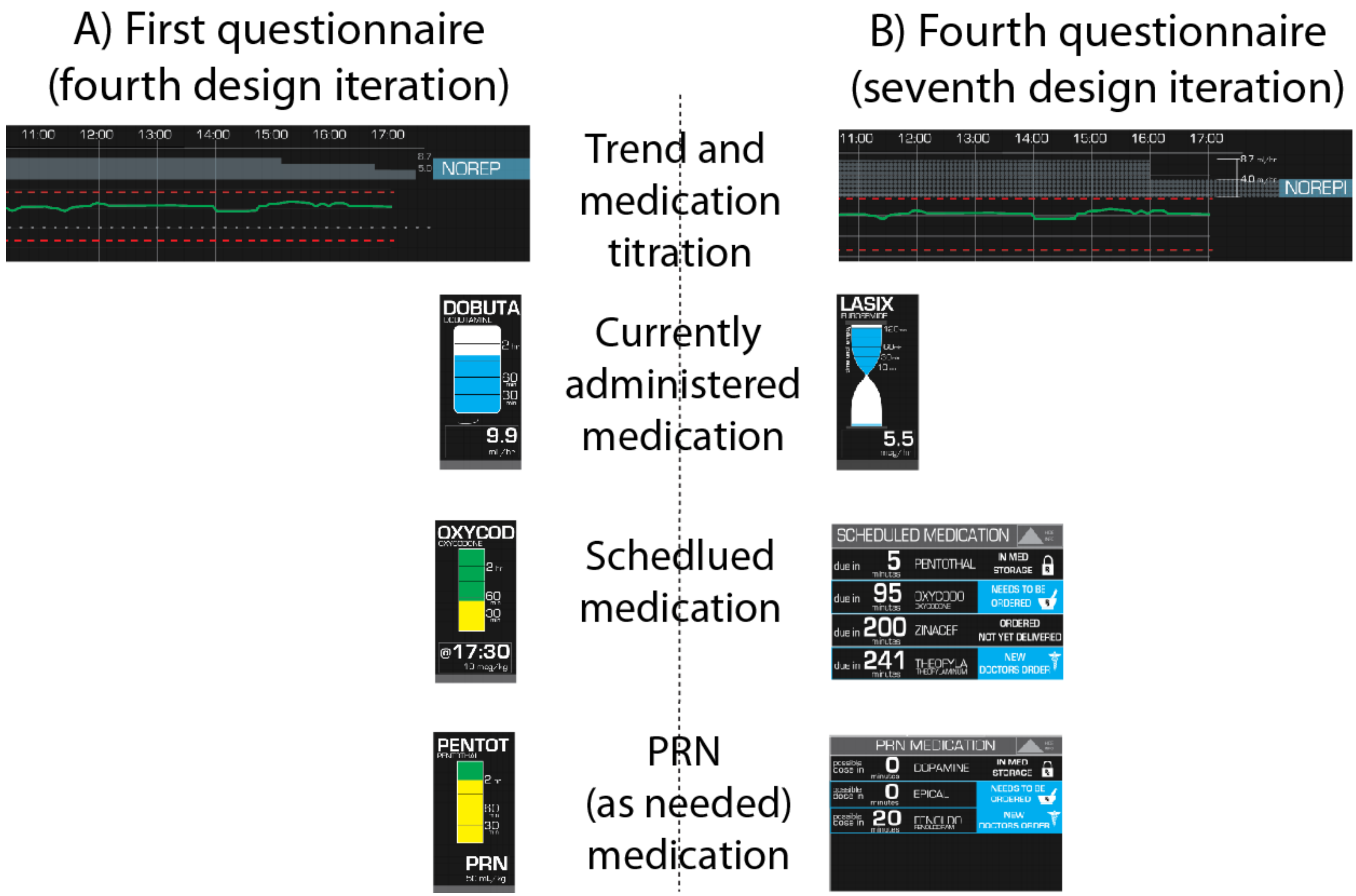

Figure 10 Changes to the seventy prototype iteration compared to the third iteration

Discussion and implications

Through the iterative design process of the integrated display, the availability and accessibility of information could be improved, and a display could be created which nurses preferred over the one they currently have.
However, it needs to be evaluated it the final display prototype can influence nurses' situation awareness e.g. by improving the availability of information. During the design phase we could not test the influence of the prototype on situation awareness, or if the prototype improves task performance time, workload, and satisfaction. Therefore, a formal evaluation of the display compared to using conventional displays was performed and is described in the following chapter.

CHAPTER 5

EVALUATION OF AN INTEGRATED

INFORMATION DISPLAY

The integrated display aimed to improve the information presentation and availability for nurses, and thereby influences environmental and computer system characteristics. It focused especially on supporting frequent and safety-critical work areas of medication management, assessment of the patient's state, and team communication. Therefore, an evaluation should focus on measuring the influence of the change in system characteristics on nurses' work.

The aim of this investigation was to assess nurses' performance when using the new information display compared to using conventional devices as a control. Objectives were to measure their a) situation awareness, b) response time, c) workload, and d) user satisfaction.

Information shown on the integrated display and included in the evaluation came from the patient monitor, the electronic medical record, a medical reference library, the ventilator, and infusion pumps. However, it still has to be shown if the integrated information display improves human performance when completing real nursing tasks.

Methods

Setting

This study was conducted at the University of Utah Health Science Center, a 383-bed tertiary care medical hospital and regional referral center. The study was performed in the Burn Trauma ICU (BTICU) in the BTICU break room. The unit was selected as the nurse manager agreed to let the unit's nurses participate during their breaks. On the unit work a total of 60 nurses and 20 nurse assistants. It has twelve beds and six nurses working per shift. Patients were pediatric and adults: thermally, chemically, or electrically injured, and from other medical fields requiring critical care services. The average daily census is about 11, annual admissions between 375-400, and the BTICU is verified as a burn center by the American College of Surgeons and is a Level I Trauma Center.

Participants

Participants were invited to participate if they were currently working at the ICU during two consecutive night shifts of the tests, and if they were working in the role of a nurse. Excluded were nurse assistants, learning nurses, and nurses who were only working a single night in a row. Night shifts were selected because nurses were less likely to be interrupted during the test and the break room was available. The institutional human subjects review board approved the study (ClinicalTrials.gov identifier: NCT00714012).

Familiarity of nurses with the displays

Nurses were asked prior to the evaluation for their experience with the control devices. The familiarity with the patient monitor was a medial of 2.3 years, the electronic medical record 3 years, and medication database 2 years. They were not familiar with the infusion pump and the ventilator. Several nurses had participated in the design of the integrated display. To compensate for possible familiarity with displays, all participants received standardized training on all displays prior to the test independent of their familiarity. The information shown on the Integrated display was completely new to nurses as it was different from the data displayed during the design phase.

Study design

The study used a counter-balanced 2 display (Control vs. Integrated) by 3 scenario (Medication management, Patient awareness, Team communication) repeated-measure design. The design was counter-balanced across display type and scenario. Each subject was exposed to one of the 6 possible combinations of the two design factors using Latin square, see Table 17.

Instrumentation

Displays

The practicability of evaluations using paper based prototypes is high – users evaluating the same device on paper and on computer screens found the same percentage of usability problems although it took them 30% longer.[113] Prototypes with varied information were used, dependent upon the questions (see Appendix C). Paper based prototypes were the method of choice because of not all data

Table 17 Presentation order of display and scenario

Participant #	First Display	Second Display	Scenario sequence		
1,7	INTEGRATED	CONTROL	A	B	C
2,8	INTEGRATED	CONTROL	C	A	B
3,9	INTEGRATED	CONTROL	B	C	A
4,10	CONTROL	INTEGRATED	A	B	C
5,11	CONTROL	INTEGRATED	C	A	B
6,12	CONTROL	INTEGRATED	B	C	A

shown on the Integrated display was available through interfaces from existing devices.

Paper based prototypes of the displays were created using Illustrator CS4 (Adobe, San Jose) and printed in the size of the original devices. Screens of each device were combined as booklets with tabs labeled according to the information provided. The first page of the booklet showed the initial device screen and the following pages showed additional screens. The initial and scrolled down screens were both included as separate tabs for devices where users had to scroll down to see information at the bottom of the screen.

Data presentation tool

Questions were presented on a custom web-based measurement tool that recorded whether the answers were correct and recorded the time taken from opening the question to submitting the answer. To simulate the time critical ICU environment, a 60sec hourglass was presented alongside with the question. If participants asked about the hourglass, they were instructed to answer as fast as possible but that their answers would be accepted even if the time expired.

Integrated display

Figure 11 shows the Integrated display prototype with vital signs, vital sign trends, alarm history, the vital signs for the nurse's second patient, medications being delivered, scheduled and PRN medication orders, medication IV compatibility and interaction, potential side effects of medications, fluid balance,

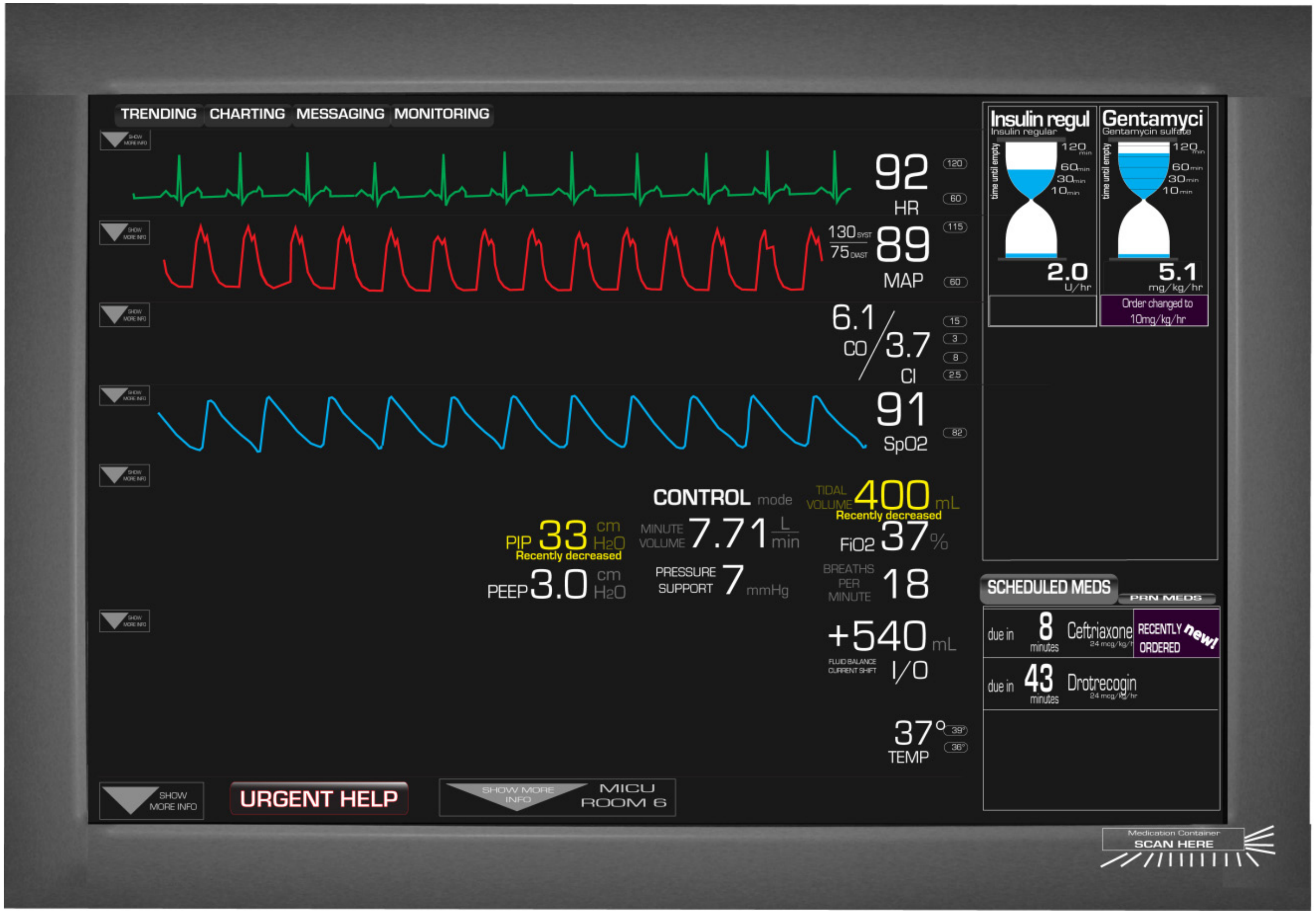

Figure 11 Integrated display - Main screen which shows vital signs, ventilator settings in the center (two were recently changed in yellow), fluid balance below, and on the right current and scheduled medication (one changed and one new order in purple

and ventilator settings. The Integrated display prototype booklet had a total of 12 screens/pages. Related information was displayed in special proximity, e.g., for medication the current rate, order, and side effects to monitor. See Appendix C for the screens of the Integrated display.

Control displays

Figure 12 shows the Control displays. Control devices were selected based on current use at the BTICU. The ventilator currently in use could not show recent changes in settings, and the current infusion pump could not display the time until the delivered medication was empty. Therefore alternate devices were selected (see below) which provided adequate functionality for the test.

The patient monitor (IntelliVue MP70, Phillips, Andover, MA) showed the patient’s vital signs on the initial screen, and on additional screens vital signs of the nurses’ second patient, past alarms, and a vital sign trend. The patient monitor prototype booklet had a total of 3 pages/screens.

The electronic medical record (PowerChart®, Cerner, North Kansas City, MO) showed the patient’s demographics on the main screen, and on additional screens fluid balance, the electronic medical record, and changes in orders. The prototype had 7 pages/screens.

The medication reference (Micromedex® healthcare series, Thomson Reuters, NY) had 19 pages. On additional screens were IV compatibility, interaction, and potential side effects of current medication, as needed medication (PRN) and scheduled medication.

Figure 12 Paper based prototypes of the Control setting. Clockwise: Ventilator, medication reference – opened at the potential side effects tab, electronic medical record - opened at the scheduled medication tab, infusion pumps, and patient monitor

The ventilator (Evita XL®, Drägerwerk, Lübeck, Germany) showed ventilator settings on the main screen and recent changes in the settings on an additional screen. The prototype had 2 pages.

The infusion pump (Outlook 100®, B Braun, Melsungen, Germany) showed the medication being delivered and the time left until it was empty on the main screen. The prototype was displayed on a single page.

Measurements and data collection

Situation awareness

Situation awareness was measured as the accuracy of participant's answer to each question.

Response time

Response Time (seconds) – the time taken by the participant to answer each test question, from when the question is presented until the participant submitted his/her answer.

Workload

NASA Task Load Index[92]– measurement of the participant's perceived cognitive workload for all scenarios was completed after using each display. NASA TLX uses six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. (Appendix F) For each dimension a score from 0 to 100 is obtained using 20 step bipolar scales. A global score can be calculated by combining the single scores with operator defined different weights.

NASA TLX was found to have a high validity and reliability with Cronbach's alpha higher than 0.80.[96] It was selected because it is easier to understand than the Workload Profile (WP),[94] and less exhaustive than Subjective Workload Assessment Technique (SWAT), [93] having a comparable intrusiveness.[95]

<u>User satisfaction</u>

QUIS[98] Version 7 part 3 (Appendix G) was used to assess nurses' perceived usability of the displays with additional free-text questions. QUIS was found to have a high reliability and validity (Cronbach's alpha = 0.94),[99] see Background.

Four free text questions were used to additionally assess nurses' opinion and experience with both the Integrated and Control displays.

- How was the availability of clinical information?
- How was your overall sense of the patient and the treatment?
- What did you like best?
- What should be redesigned?

Scenarios

For the evaluation we used a direct experimental technique to measure nurses' situational awareness and their understanding of the situation. We employed an adaption of the Situation Awareness Global Assessment Technique (SAGAT) [82, 83] (see Background) with multiple choice questions organized in three scenarios which were answered at the participant's own pace.

17 questions were developed by the author in consultation with a psychologist and ICU nurses (see Appendix C). They covered the three levels of situation awareness: Perception was defined as recognition accuracy of values on the displays, comprehension as accurate situation model, and projection as the accuracy of future estimation of events.

Questions were deliberately created to be complex with a high number of simultaneous medications, multiple screens to look at and addressing information presentation deficits in the Control devices. Such deficits were e.g. that scheduled continuous infusions almost looked identical as running infusions, that medication interaction was listed alphabetically ordered by the first interacting medication, and that trends were hard to discriminate due to the small and overlapping display areas.

Questions were organized in three scenarios and covered the most frequently performed and patient safety critical task areas identified in the observation study (Chapter three). Each scenario had 5-6 questions with 4-6 answer options each. Answers included the option "I do not know," "None" or "None of the above." for the majority of questions.

The three scenarios were medication management, patient awareness, and team communication and are described in the following in further detail.

Medication management

A busy colleague asked the participant to administer a medication through the same line as currently in use for other medications. The participant was asked to identify the drug name, dose and potential drug-drug interactions of the next PRN medication. An example using both displays for medication administration is shown in Figure 13.

Patient awareness

The participant was asked to assess the patient's condition using past alarms, vital signs values and fluid balance. The participant was asked to assess the condition of the nurse's second patient (in the adjoining room) without leaving the current room.

Team communication

The participant was asked to identify changes made by another health care team member to ventilator settings and medication orders. The participant was asked to tell a colleague which infusion pump medication needed to be refilled and which PRN medication was due within the next 20 min.

Verification of scenarios

Three ICU nurses reviewed the scenarios prior to the evaluation and verified that questions could be answered when using the prototypes. They adapted the scenarios to nursing language and improved scenario realism. They then rated

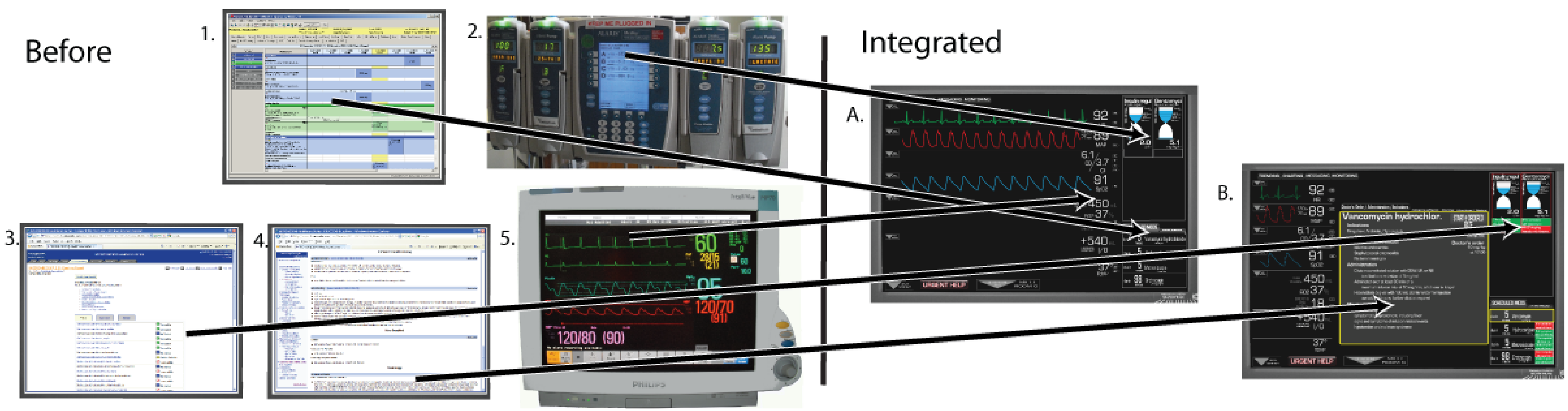

Figure 13 Example of display-interaction for medication administration with the currently used devices at ICUs (Before – Control devices) and display interaction using the Integrated display (Integrated). Arrows indicate the new location of the information.
Before (Control devices): Currently, different devices are used to show 1. the medication order, 2. medication being delivered, 3. medication compatibility, 4. potential side effects, and 5. the patient's vital signs.
Integrated: On the Integrated display, related information is displayed in close proximity. A. Nurses see the medication order directly. B. They scan the new medication and automatically see medication compatibility with current medication, potential side effects, and vital signs.
[Human Factors and Ergonomics Society 54th Annual Meeting, San Francisco, 2010. "Integrated Information Displays for ICU Nurses: "Field Observations, Display Design, and Display Evaluation", S. H. Koch, N. Staggers, C. Weir, J. Agutter, D. Liu, D. R. Westenskow. Submission ID: 429 Reprinted with permission of the Human Factors Society.]

the scenarios to be realistic 6.5 (1=unrealistic and 7=realistic), clear 5.25 (1 = unclear … 7 = clear), and comprehensive 5.25 (1 = not comprehensive …7 = comprehensive), and reached the final cut of score of 5 for the evaluation.

Procedures

Nurses participated in the study during two consecutive nights. During the first night by using the first display, and during the second night using the remaining display (see Table 17). During the first night, participants were consented as required by the institutional human subjects review board (ClinicalTrials.gov identifier: NCT00714012).

Prior to the study, participates received standardized training using all devices and all relevant functions and screens for the study through a self paced power point presentation. They subsequently answered a competency test. In case they answered all competency questions correctly they proceeded with the study. If they did not answer all questions correctly they received additional training and repeated the competency test. Failure to complete the test a second time was an exclusion criterion.

During the study display prototypes were presented on a table. Participants read a clinical situation on a computer screen, looked at the paper-based displays, and answered the questions.

After using each display, nurses completed the post tests NASA TLX, QUIS and answered free text questions.

During the next night nurses performed the second part of the study by using the second display (see Table 17). The same procedures were used as described above: Nurses received standardized training on the second display, passed the competency test, participated in the study with the second display, and answered post-tests questions about the second display.

Data analysis

All statistical analysis was performed using Matlab analytical software (release R2008b, The MathWorks, Natick, MA).

Fisher's exact test suits for the analysis of small categorized samples, and its assumptions are a directional hypothesis, independent observations, random sampling, and dichotomous observations.[114] Fisher's exact test did not allow simultaneous analysis for effects and interaction effects, so pair wise comparison and Bonferroni correction was used. Results of Fisher's exact test are p-values.

Repeated measure Friedman's ANOVA is a non-parametric test that suits to analyze data that are not normally distributed and which has no equality of variance. It uses the ranks of the data rather than their raw values.[115] In Matlab Friedman's ANOVA exact test does not allow simultaneous analysis for effects and interaction effects through a single analysis, so pair wise comparison and a Bonferroni corrected α-critical were used. Results of Friedman's ANOVA are p-value and χ^2-values.

Situation awareness

Fisher's exact test was calculated for the accuracy of the decision representing situation awareness. We used a 2x3 Fisher's exact test comparing the two displays for all three scenarios at a Bonferroni corrected α_{crit}0.05/3=0.0083. Additionally we calculated a 2x3 Fisher's exact test comparing the two displays for all three levels of situation awareness at a Bonferroni corrected α_{crit}0.05/3=0.0083.

Response time

Our measured response time neither met the assumption of normality nor of equality of variance for the standard 2x3 ANOVA. Therefore, we used a repeated measure Friedman's ANOVA (α =0.05). Seven comparisons of response time (global times, times the three scenarios, and times for the three situation awareness levels per display) were performed using a Bonferroni corrected α_{crit}=0.05/7= 0.0071.

Workload

Our measured data for workload scores neither met the assumption of normality nor of equality of variance for the standard 2x3 ANOVA. Therefore a repeated measure Friedman's ANOVA (α =0.05) was calculated. Additionally for workload the summed sub scale workload was calculated using equal weights for each sub scale.

<u>User satisfaction</u>

Our measured data for the QUIS scores neither met the assumption of normality nor of equality of variance. Therefore, we used a repeated measure Friedman's ANOVA (α =0.05). Nurses' answers to the free text questions were classified into the two categories positive and neutral/negative by the author.

Results

Twelve BTICU nurses (8 female, 4 male) with a median age of 31.5 years (range 23 - 57) participated. They had worked in an ICU setting for a median of 3 years (range1 – 24 yrs). Their median nursing expertise was 7 (1=novice, 9=expert), competence 7 (1=low competence, 9=high competence), and confidence 7 (1=low confidence, 9=high confidence). Participants were using computers on average 5 hours per day.

Two participants had to repeat the training and quiz before entering the study, but no one was excluded. The median study duration was 23 min (range 15-47 min).

Situation awareness

The average situation awareness level for the Control displays was 65% (ranging from 47% to 71%), and 86% with the Integrated display (ranging from 71% to 94%) Using the Integrated display nurses made their decisions 21% more accurate than using the Control displays.

Table 18 shows the pair wise comparison of the correct answers to the

Table 18 Pair wise comparison to analyze main effect and interaction effects for situation awareness level and scenario (Fisher's exact test). Significant results are marked by asterisks (p≥0.001). Additionally the table indicated percentages of correct situation awareness questions

	Control	p	Integrated
Overall	65% (132/204)	<0.001*	86% (175/204)
Perception * Display	65% (50/60)	<0.001*	89% (64/72)
Comprehension * Display	68% (41/60)	0.006*	90% (54/60)
Projection * Display	61% (44/72)	0.028	79% (57/72)
Medication management * Display	40% (29/72)	<0.001*	81% (58/72)
Patient treatment * Display	74% (53/72)	0.107	85% (61/72)
Team communication * Display	83% (50/60)	0.153	93% (56/60)

situation awareness questions for display, scenario and situation awareness level. Statistically significant results were found overall (p=1.1E-6 Fisher's exact test), for medication management (p<0.001), perception (p<0.01), and comprehension (p=0.06). The overall accuracy for the medication management scenario was 60% and for situation awareness level projection 70% indicating problems with this scenario and this situation awareness level. Situation awareness levels and scenario are correlated.

Figure 14 shows the accuracy of answers to situation awareness questions by scenario and situation awareness level graphically. Table 19 shows the results for the questions that were answered incorrectly more than half the time.

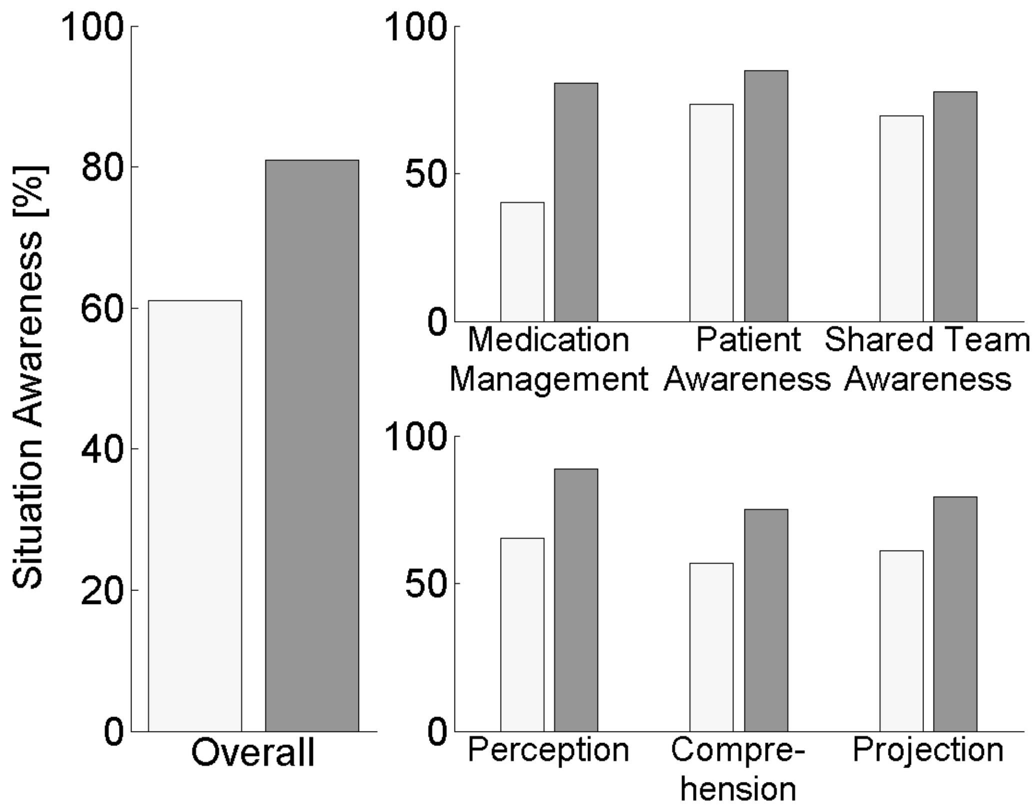

Figure 14 Situation awareness answer accuracy. White=Control, grey=Integrated

Table 19 Questions answered incorrectly half of the time or more. The question numbers (e.g., A2) refer to the Appendix where all questions including correct answers are reported

Question	Control incorrect	Integrated incorrect
A2: “Please check which medications need to be administered within the next 5 minutes.”	12/12	0/12
A4: You decide to administer Metronidazole and Drotrecogin together with the currently infusing meds (Hydrocortisone and Vancomycin). However, as the patient has only 2 lines you need to decide which of the lines to use. For which of the following medication combinations do you expect to see IV in-line incompatibility? Assume that not tested meds are incompatible.	9/12	5/12
A3: The attending is concerned that pharmacy has not checked drug-drug interaction for Gentamycin as the order was rushed. To protect your patient: Do you expect future drug-drug interaction while administering Gentamycin together with the currently infusing meds (Hydrocortisone and Vancomycin)?	8/12	4/12
B3: “Based on the SPO2 value during last HR alarm: What would you expect the first patient’s SpO2 level to be if there was another HR alarm in the future?”	8/12	4/12
A6: “The patient says he has nausea and pain - please push a PRN medication. What issues are you most concerned about in this situation?”	7/12	4/12
A5: “Which of the following side effects of the currently administered medication Insulin and Gentamycin would expect to see and monitor?”	6/12	0/12

Response time

Table 20 shows the pair wise comparison of the response time for display, scenario and situation awareness level. The median response time for the Control displays was 34sec (SD 51, ranging from 5.7 sec to 523 sec), and 25sec for the Integrated display (SD 26, ranging from 5.9 sec to 251 sec). Using the Integrated display nurses made decisions 26% faster than using Control.

Nurses overall response time was significantly faster when using the Integrated display (p=1.8E-7, χ^2=27.25, repeated measure Friedman's ANOVA). Among scenarios, medication management and team communication were answered significantly faster. Among situation awareness levels, perception questions were answered significantly faster (repeated measures Friedman's ANOVA). Table 21 shows the raw response time per display, scenario and situation awareness level, see also Figure 15 for a graphical representation. Situation awareness levels and scenarios are correlated.

Table 20 Pair wise comparison to analyze main effect and interaction effects for response time (repeated measure Friedman's ANOVA). Significant results are marked with asterisks (p≥0.001)

Factor	p	χ^2
Display	<0.001*	27.25
Perception * Display	<0.001*	17.51
Comprehension * Display	0.011	06.41
Projection * Display	0.035	4.42
Medication management * Display	0.001*	12.67
Patient treatment * Display	0.035	4.43
Team communication * Display	0.001*	10.21

Table 21 Median response time (α-critical = 0.007). P-values are calculated using repeated measure Friedman's ANOVA

	Control (sec)	Difference (sec)	Integrated (sec)
Display	34	9	25
Perception * Display	29	11	18
Comprehension * Display	34	9	25
Projection * Display	49	18	31
Medication management * Display	54	16	38
Patient treatment * Display	30	3	27
Team communication * Display	24	8	16

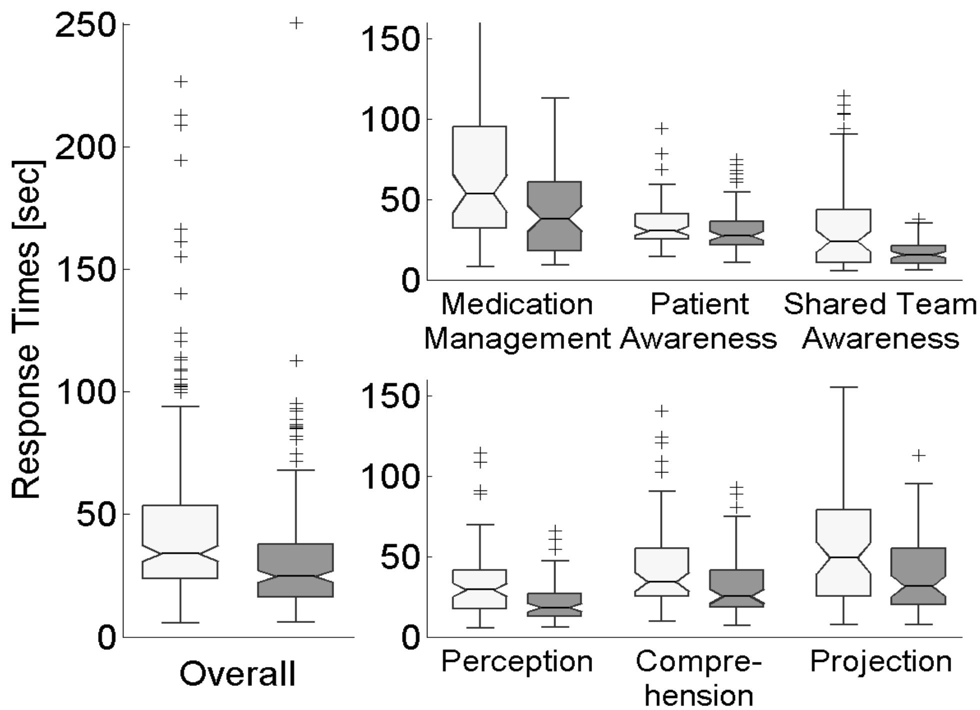

Figure 15 Response time -Time from seeing question until answer was submitted. White=Control, grey=Integrated

Workload

The summed workload score was better for the Integrated display (7.1) than for the Control display (9.9). The median TLX score for the Control displays was 11 (ranging from 1 to 20). The Integrated display got a better median score of 5 (ranging from 1 to 18).

Table 22 shows that nurses reported significantly less effort ($p=0.03$, $\chi^2=4.45$, repeated measure Friedman's ANOVA) and lower frustration ($p=0.01$, $\chi^2=6.4$) when using the Integrated display. The other measures of workload did not show a significant difference. Figure 16 shows the data graphically.

User satisfaction

The median QUIS score was lower for the Control displays (5.2, ranging from 2 to 9). The Integrated display got a higher median score of (7.7 ranging from 2 to 9).

Table 22 Pair wise comparison of analyze effect of workload (repeated measure Friedman's ANOVA). Significant results are marked with asterisks (p≥0.05)

NASA TLX measure	Control (median)	p	χ^2	Integrated (median)
Mental workload	14.5	0.13	2.27	8.5
Physical workload	4	0.3	0.81	3
Temporal workload	12.5	0.2	1.60	7.5
Performance	6.5	0.5	0.4	5
Effort	14.5	0.03*	4.45	8.5
Frustration	10.5	0.01*	6.4	3.5

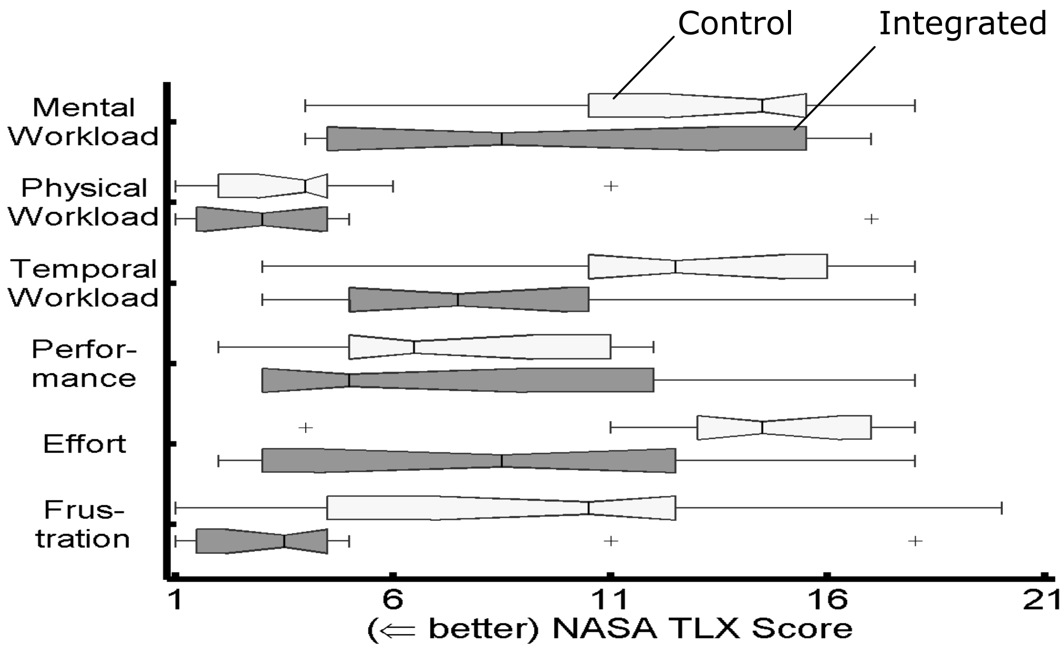

Figure 16 Perceived workload (NASA TLX)

Table 23 shows the analysis with repeated measure Friedman's ANOVA. Significant differences existed for the dimensions Terrible…wonderful (p=3.9E-7, χ^2=8.3), Frustrating…satisfying (p=6.7 E-3, χ^2=7.36), Dull…stimulating (p=0.02, χ^2= 5.33), and Inadequate power…adequate power (p=3.9E-3, χ^2=8.33). See Figure 17 for a graphical representation of the data.

<u>Free text questions</u>

There were more positive comments for the Integrated display than for the Control display (see Appendix E for all answers). Positive answers about the availability of clinical information were 11 vs. 5 (Integrated vs. Control), e.g., "Great. It is very helpful to have all different kinds of information available from one source- instead of having to look several different places and compare." Equally higher was the number of positive comments about the sense of the patient 12 vs. 5 (Integrated vs. Control). An example tor such positive comments could be “I felt like I had the information I needed to make the best informed decision.”

Table 23 Pair wise comparison of analyze effect of user satisfaction (repeated measure Friedman’s ANOVA) Significant results are marked with asterisks (p≥0.05)

QUIS measure	Control (median)	p	χ^2	Integrated (median)
Terrible…Wonderful	5.5	0.01	8.33*	8.5
Frustrating…Satisfying	4	<0.01	7.36*	8
Dull…Stimulating	5.5	0.02	5.33*	8
Difficult…Easy	5	0.5	0.4	7.5
Inadequate power… Adequate power	5.5	<0.01	8.33*	8
Rigid…Flexible	4.5	0.56	0.33	8

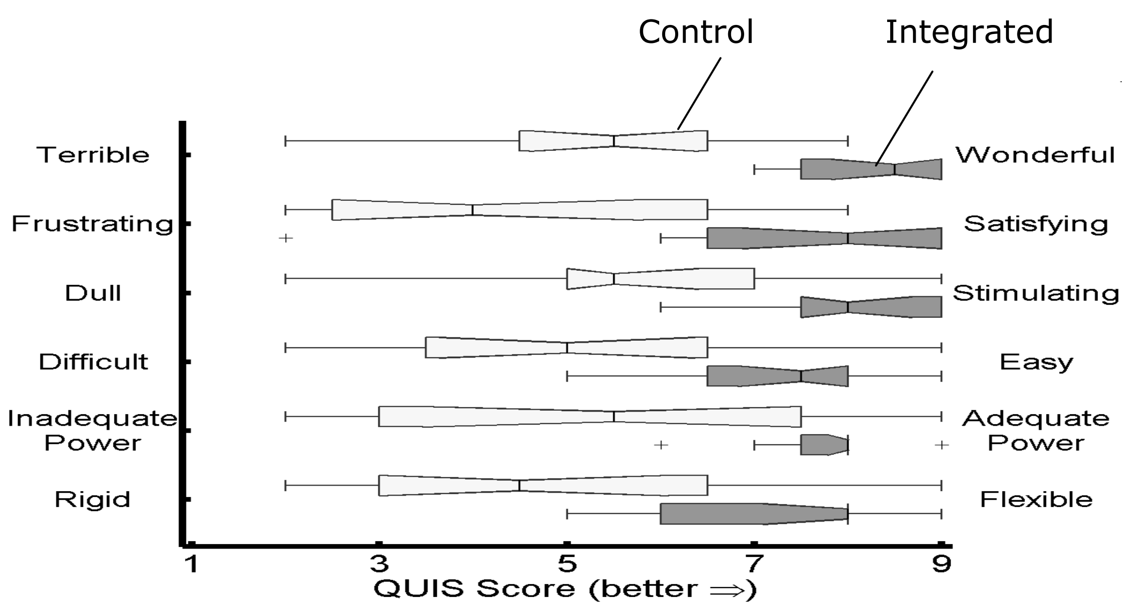

Figure 17 User satisfaction - overall reaction to the display (QUIS)

CHAPTER 6

DISCUSSION

We conducted a set of three studies for the purpose of designing an efficient and effective ICU display to improve ICU nurses' situation awareness through addressing deficits in the user's environment characteristics (see Background, Figure 1).

During the first study (Chapter 3) we observed and classified frequent nursing tasks, researched patient safety critical tasks, and identified challenges for nurses' situation awareness. We could identify that nurses were performing medication management tasks, patient monitoring tasks and communication tasks most frequently (Table 1), and rated these tasks to be most critical for patient safety (Table 5). Challenges during these tasks for nurses' situation awareness were found to be that task-relevant information was often presented in the wrong format, or unavailable at the point of care and laborious to obtain. Additionally, nurses were sometimes unaware of significant changes in their patient's status and equipment operation (Table 2-Table 4). We then assumed that nurses might benefit from integrated and improved information display.

During the second study (Chapter 4), we designed an integrated information display which presents all of the information needed by nurses at the patient bedside. It addressed limitations in the user's environment characteristics and integrated information from the patient monitor, the ventilator, infusion pumps, the electronic medication record, and a medication reference database. Nurses selected a display based on the information organization of existing patient monitors, with added medication management and team communication features. The correct information extraction and intuitiveness of the information display could be improved based on nurses' feedback and increased adherence to human factors display design principles.

The evaluation of paper-based prototypes during the third study (Chapter 5) of both the Integrated display and conventional displays showed that nurses could answer questions about the patient's status and treatment faster ($p<<0.05$), had a higher situation awareness ($p<<0.05$) using the integrated display. They had a significantly higher situation awareness answering questions covering perception, comprehension, and medication management. Their response time was faster ($p<<0.05$) using the integrated display. Significantly faster answers were made for perception, medication management, and team communication questions.

First we will interpret the findings of each study, then we will discuss limitations for each study, followed by implications for practice, future work and concluding remarks.

Interpretation of the findings

Using an integrated display might improve nursing care, lead to fewer errors, and help the patient receive the right therapy at the right time.

Identification of requirements

Our results show that our observations, questionnaires and affinity diagrams allowed identifying task frequency, patient safety relevance of tasks and requirements for an integrated display according to the first aim. The main focus of an integrated display was identified to be medication management and communication of changes in treatment and patient condition. An integrated display should address the following deficits and challenges for nurses' situation awareness: 1) The need to gather information from multiple devices such as the vital sign monitor, IV pumps, the ventilator, and electronic medical records. 2) Information about drug-drug compatibility and adverse side effects was not available at the bedside. 3) Patient orders were changed without notification. 4) Equipment settings were changed without notification.

Comparing task frequency with patient safety relevance, the most frequently performed category of nursing work – communication - was only rated third for patient safety. Reasons might be that frequently performed tasks might not always be safety critical. Charting which was the most frequent task was rated to have very low patient safety relevance. Possible reasons for this finding could be that nurses might not see immediate value in documentation.

The high patient safety score for nursing tasks (average 6.0 on a Likert scale ranging from 1 "not important" to 7 "very important) might imply that nurses perceive most of their tasks as extremely patient safety relevant. All tasks had a high score (above 5) except bathing (4.8).

Comparison with the literature

Our results are based on a modification of participant observation, questionnaires and brainstorming to define display requirements. Other researchers used cognitive work analysis[100, 101] or expert consultation to identify requirements for nurses' bedside displays.[41, 102] Cognitive work analysis might have resulted in more in-depth findings than our results. Expert consultation might have limited our results to problems the users manage to recall without being in the context of work.[61] Our methods might be the “happy medium”. Similarly to cognitive work analysis we looked at tasks nurses performed, the decisions they made, information behavior, and context in which they performed their work, and asked them about safety relevance comparable to expert consultation.

Improved information access is demanded similarly by other research.[4, 19, 116] Our desire to improve communication with other clinicians is shared by other researchers.[37, 117, 118] Synchronous communication between nurses and physicians increases shared knowledge and nurses’ understanding of the patient state.[119] Our demand for trends which allow simultaneous reviewing of changes in drug delivery and alarm settings, is equally demanded by other researchers.[9] Proactive and reactive approaches to nurses’ work have been identified previously.[120-122]

The majority of the task categories we defined are comparable with other research,[37, 38] however, the rest was specific to our research focus. Although, our task categorization was verified by ICU nurses, other researchers ordered tasks in a different way. For example communicating with the patient to educate about medication use or calling the doctor to clarify orders were classified as communication tasks; however, alternatively both could have been classified as medication-related tasks.

Task categories defined by Hendrich et al.[38] who observed medical surgical nurses were slightly different to ours. In their study, documentation tasks had their own category – in our study they were part of team communication. Additional categories in Hendrich's study were waste (waiting, looking/retrieving, delivering), unit related functions, and nonclinical functions (personal time, patient/family care, administration/teaching). Tang et al.[37] observed remote monitoring tasks performed by ICU nurses – and did not categorize according to medication management, organization, and care tasks. Additional categories they defined were miscellaneous, maintaining records, and use of technology. Our categorization of tasks into task categories is one of many ways of ordering task ICU nurses perform. These differences might imply that remotely monitoring nurses perform different tasks, and task categories depend on the focus of the research.

Some task frequencies we observed were comparable to task frequencies identified by Görges et al.[36] who observed nursing tasks performed inside of ICU rooms. His group focused on tasks which might possibly cause alarms in intubated and ventilated medical ICU patients. For medication administration, their observed frequency was similar to ours (1.5/hr), as well as for suctioning the patient's airways (0.4/hr), and oral care (0.1/hr). However, their charting frequency was lower (0.7/hr vs. 1.7/hr) – possibly because nurses used paper charts in their observations vs. computers during our observation. Furthermore, their patient assessment frequency was lower - (0.4/hr vs. 1.1/hr) possibly as they combined multiple tasks into one assessment. Other tasks they reported were categorized differently in our study and are therefore not comparable.

To confirm our findings of patient safety critical tasks in the areas of medication management, patient monitoring, and communication, no study with comparable scoring by nurses was found. A study by Rothschild et al.[3] analyzed the incidence and nature of adverse events and medical errors at ICUs – their focus was on errors occurring all over the ICU, not only involving nurses. Rothschild et al. found that 61.4% of serious errors were associated with medication ordering or execution of treatment, 14.8% with inadequate reporting or communication, and 9% based on inadequate monitoring systems or inadequate patient assessment. Other reasons they reported for serious medical errors were categorized differently than in our study (e.g. failure to follow protocol to prevent accidental injury) and are therefore not comparable. Rothschild's findings correlate to our findings of patient safety critical tasks, and might confirm that the tasks used in the questionnaire were sufficiently representative and the methodology of asking nurses to indentify safety critical tasks was adequate.

Nurses were previously found to gather and combine information from multiple devices such as vital sign monitor, IV pumps, ventilator, and electronic medical record,[4, 123] and to have general information deficits during medication management.[85] Furthermore, previous research confirms that changes in orders were noted too late[39] or insufficiently communicated,[39, 117, 124] and that ICU nurses struggled to be aware of patients while away.[125]

Our research adds to literature by identifying that nurses' access to information about medication compatibility and adverse drug effects is sometimes difficult to obtain and time consuming, and that ICU nurses were sometimes missing access to laboratory test results at the point needed. Furthermore, we found that ICU nurses were not aware of changes in equipment settings which were altered without their notification. In addition, our research adds implications for the design of integrated displays for the ICU bedside for nurses based on observed information deficits. Moreover, we could identify the patient safety relevance of nursing tasks, and challenges for nurses' situation awareness through missing information during these tasks. Our findings will allow further improvements in the communication of information at the ICU bedside to increase nurse's situation awareness.

Development and fine tuning

Our results show that prototype interviews combined with questionnaires allowed the development and refinement of an intuitive integrated information display to support frequent and patient safety critical nursing tasks at the bedside - according to the second aim (Chapter 4). The methods identified nurses' preferred information organization, information content and improved intuitiveness and correct extraction of information from the display.

The preferred information organization was found to resemble conventional patient monitors with added information for medication management, more information appearing upon interaction, and sparse use of color. The preferred information content for medication management was the order, last time given and time started, as well as associated laboratory test results, concentration of active ingredient, and maximum infusion rate dependent on the patient's metabolism. Furthermore, preferred information for trending was identified to be past alarms, values and duration. Finally, nurses wanted automatic communication of changes in treatment and patient state.

We showed that increased application of human factor's design principles and an iterative user centered development with intermediate evaluations could increase intuitiveness, correct extraction of information. This process resulted in a display with a high perceived usability.

Comparison with the literature

Nurses' preferences for a familiar looking information organization with parsimonious data content might be explained by other research which found that users prefer what they know and dislike change.[68] These findings are comparable to results of a pilot study[73] where nurses selected a familiar looking display over a more sophisticated information organization with more functionality. Usability design principles suggest that a familiar design should be changed gradually in order to be accepted.[126] In such a way, nurses could have practiced with novel information organization ideas and might have seen the advantages of other information organizations, as in our design process they were naïve to novel information organization ideas.

For patient monitoring, we found similar variables and information content to other research which identified these preferences through structured interviews.[42] They found that for cardiovascular monitoring, nurses wanted to see heart rate, arterial blood pressure, vasoactive drug infusion rates, central venous pressure, and pulmonary capillary wedge pressure. For respiratory monitoring, nurses determined mode of ventilation, artificial ventilation rate, spontaneous ventilation rate, minute volume, O_2 saturation, fractional inspired oxygen, as well as peak and expiratory pressure. For fluid management the nurses in this study desired the cumulative and hourly fluid balance, hourly fluid input and output, and hourly urine and non-urine output. To support their awareness of temperature, nurses wanted core and peripheral (skin) temperature. Possibly different interview methods do not influence findings greatly.

One surprising finding in our research was that our nurses preferred to access information on additional screens on the same device – depending on the task they wanted to do - instead of on one high density screen. This finding is comparable to results of Miller et al.[72] who found that nurses could better identify changes in the patient when using information separated by physical function on multiple screens rather than when all information was placed on a single page. However, other research found that with more practice using a display nurses preferred displays with more information content to displays with less dense content.[45] Our findings might have been influenced by the nonexistent practice time nurses had with our displays, as users who have a longer familiarity with novel designs rather prefer a higher information density to switching between screens.[71, 127]

The improved intuitiveness and the correct extraction of information and increased usability suggest that user centered development is beneficial for nurses. This is similar to findings in the development process of Wachter et al.[33]

who found that intuitiveness increased – however, during Wachter's development process diagnostic accuracy decreased. A possible explanation might be the increased application of the human factors design principles labeling,[7, 53] communicating in the user's language,[7] saliency of relevant information,[53] and pictorial reality.[55]

Our research adds to the literature by identifying nurses' preferences on information organization and content for an integrated display at the bedside. Furthermore, we could show that design for nurses which increasingly follows human factors design principles is beneficial for intuitiveness and correct extraction of information. These findings will facilitate the design of information displays for ICU nurses.

Evaluation

Our evaluation showed that the integrated information display improved nurses' situation awareness, response time, workload, and user satisfaction and as intended in aim three (see Introduction) compared to using conventional devices as control. Nurses' situation awareness was significantly higher overall, during perception and comprehension questions and during medication management questions. Their response time was faster overall, during perception questions, during medication management and team communication.

During medication management, nurses' improved situation awareness and shortened response time might be due to the emergent medication features giving the nurses just-in-time information regarding changes in the current status of the treatment. In particular, the immediate notification of changes in a medication order might have been salient enough for the nurses to instantly focus on the task at hand. Another salient emergent feature was the countdown for currently administered, scheduled, and PRN medication. The high number of incorrect answers (60%) during the Control scenario of medication management might be partially due to the fact that questions were addressing information presentation deficits on the Control displays and requiring nurses to combine information from multiple screens. Using the integrated display might eliminate some errors based on such information presentation deficits and possibly more errors could be prevented.

During perceptional tasks, nurses' higher situation awareness and shortened response time and their faster response during comprehension questions might be due to information in a single location, and direct visibility of relevant information. A single information location often allowed nurses to find the answer to a question directly instead of checking multiple screens simultaneously. They did not have to combine information from multiple locations to understand the patient and treatment: to understand the "big picture" all relevant information appeared consolidated and close to each other in a "one-stop-shop". The direct visibility of relevant information showed important information on the initial screen of the Integrated display instead of hidden on additional screens which have to be reached through complex menu structures (or by opening a tab in our test).

During nurses' projection tasks no significant difference was found. This might indicate that integrated information display does not influence the future prediction of patient developments. One reason might be that prediction of developments might possibly depend on expertise rather than on the availability of information.

Contributors to the success of the display might have been the emergent features giving the nurses just-in-time information regarding changes in the current status of patient and treatment. In particular, the immediate notification of changes in a medication order must have been salient enough for the nurses to instantly focus on the duty at hand. Another salient emergent feature was the countdown for currently administered, scheduled, and PRN medication which allowed nurses to easily predict future actions.

Comparison with the literature

The increase in user's situation awareness in perception and comprehension suggests that combined presentation of values on a single device and organization of values according to nurses' preferences and needs helps nurses to be better aware of information. This finding is consistent with other research[20-23, 128] Better situation awareness could similarly be a reason for other findings of increases in accuracy[24, 25, 29] and enhanced detection of patient change[27, 72] when using novel displays.

Our finding of shortened response time when using a novel data representation is similar with other research.[25, 26]The shorter response time during medication management and team communication might be correlated with the fact that for these tasks most information was visible on the main screen of the integrated display, whereas for patient treatment information had to be obtained from subsequent screens.

Our finding of reduced workload overall and for the subscales frustration and effort TLX is partially confirmed by other research. For a mixed numerical–graphical Charabati et al.[129] found a significantly lower NASA TLX compared to an enhanced graphical display or a numeric display. Agutter et al. found reduced perceived workload in participants using a graphical visualization for arterial blood gas compared to a traditional monitor.[29] Albert et al. found no effect of a graphical display compared to a numeric display on workload. [31] Drews et al.[89] found significantly higher workload values for performance – but no difference in other subscales.

Our research adds to the literature by showing that for nurses an integrated information display increases situation awareness and satisfaction, and decreases response time and workload.

Limitations

As all nurse participants in the design and evaluation process were from the same hospitals, and evaluations were performed only with BTICU nurses, the selection effect might limit the generalizability of our findings. Therefore, the integrated display might address and solve specific problems in this hospital but the results might have a limited generalizability. However, nurses from the BTICU were treated patients including medical and surgical patients, and devices used in the BTICU are similar to the devices nurses in other ICUs use, so our results might translate to ICUs in general where nurses are using the tested Control devices.

The only validated questionnaires in the project were the ones used during the evaluation – the questions used in the other questionnaires were not validated. This might limit the validity and reliability of our findings during requirements identification and design of the prototypes.

The theoretical model we used might limit out study. As discussed in the Background, one limitation of Endsley's situation awareness model is the missing of a temporal component. During our design and evaluation, the users' practice with the new display was not taken into account. However, as practice increases performance and changes preferences, the limited practice users had with the displays might decreased generalizability of our results (see below).

Identification of requirements

Our observation period was largely between 8am and 1pm, so we might have observed tasks with a different frequency than in a 24 hours observation study and we could have observed more challenges and infrequent tasks. Other researchers have found the timeframe between 10am and 1pm to include the most human errors. Infrequent nursing activities were found to occur between 6 am and 10 am.[21] Observations in a different setting, i.e., in a hospital equipped with different devices might have resulted in other challenges. For example, some of the information availability challenges might have been solved by existing solutions, e.g., handheld devices or PCs on wheels.

To identify patient safety relevance of tasks, we relied on nurses' opinion on a sample of tasks but not all tasks nurses perform. Our findings might be limited by nurses' perception that difficult tasks might be more safety relevant than easy tasks. Using a different methodology could have resulted in different findings.[130] Furthermore, the selection of representative tasks from each nursing work area was performed by a single nurse. A different selection of tasks or questionnaires distributed to a different user group, e.g., physicians, might have resulted in different safety ratings and a different focus for the final display. Another methodology, such as interviews, might have allowed to adapt questions and their wording to individuals' needs and allowed probing issues in depth with follow-up questions.[106, 131]

Development and fine tuning

Four nurses evaluated the first prototype iteration. With such a small number of participants individual participants might have a large influence on the display evaluation - although Holtzblatt et al.[61] suggest four users per prototype interaction are sufficient.

Another limitation might be that users were asked for their preferred display, which might result in a design solution that only partially addresses underlying problems. Research found that users know which problems they have but are less proficient in identifying the optimal solution for the problems.[61, 68]

The environment during the interviews in an ICU break room with inherent interruptions could have had an impact on nurses' attention. At times, two nurses simultaneously evaluated prototypes and they might have heard and influenced each other's answers. However, each had a separate interviewer and was at a different stage of the interview.

Inadequate practice with the new display might limit validity of the results. However, practice was found to influence nurse's preferences and performance with systems, e.g., to prefer displays with higher information density.[45] As our users did not have adequate practice with the system, the validity of our findings might be limited to inexperienced users of the integrated display.

Through the static format of questionnaires we could not quantify interaction in the second part of the development phase. As interaction contributes to usability, our results do not cover all aspects of usability tests. However, measurement of these factors might have lead to further changes in the display.

Selection bias or interaction might have influenced the findings. First, participants could have completed both the first and fourth questionnaire and could have learned how the display works. However, the correct answers were never revealed, and a nurse who might have misunderstood something in the first display might have selected the same wrong answer in the final display. Interaction among participants could have lead to biased results, because the completion of questionnaires was not monitored. In that sense nurses could have asked other nurses for their help while completing the questionnaire. However, each questionnaire asked nurses to complete it alone without the help of others.

Evaluation

The generalizability of our results might be limited through the evaluation of paper based prototypes instead of actual medical devices. Paper prototypes were used because the integrated display requires functionality which is currently not yet available in all existing medical devices, e.g., bidirectional communication.[132] However, usability evaluations using paper based prototypes compared to evaluations of the same device on computer screens were found to reveal the same percentage of usability problems although it took them 30% longer.[113] In addition, paper prototypes provide different access to information than real devices.[133] Therefore, we assume that level of situation awareness and time measurements could be seen as course indicators of real world performance. To be estimates for realistic time measurements, our numbers might have to be reduced by 30%.

Time pressure was induced through a one-minute-hourglass next to each question to simulate the time critical ICU environment. If nurses asked about its function they were instructed that their results were accepted independent of the shown time, but that they should try to answer as fast as possible. The hourglass might have lead to hurried answers – comparable to the high stress ICU environment. The inclusion of the hourglass and the explanation of its function only to nurses who asked might have introduced variability into our results: some nurses may have responded to the high time pressure while some might not. Hurried answers could be incomplete because nurses might not have thought through answers or might not have collected all necessary data. As nurses asked during the test, the felt time pressure and the nurses' reaction might have been different prior to the question than after the question.

Nurses' unfamiliarity with two devices in the Control setting (infusion pump, and ventilator) might have lead to decreased performance using these devices. However, all nurses received an equal standardized training with all devices used in the Control and integrated settings. They were equally trained on familiar and unfamiliar devices and had to pass a review test before proceeding to the real evaluation. Furthermore, the integrated display was completely new. As their test performance using unfamiliar devices was better than their average performance (10 vs. 7 questions correct), we assume that unfamiliarity with the devices in the Control setting was not an issue.

Nurses were asked to identify medication interaction, a task which is normally performed by pharmacy and by nurses only in emergency situations. However, as the design was counter-balanced they had to answer the question with both displays, and the influence on the findings might be balanced.

The validity of the summed sub scale for workload is limited, as the workload score was calculated using equal weights and participants were not asked to weight sub scales.

Future research might learn from the limitations of our studies, and learn from our lessons - address some of the limitations prior to the study as discussed in the following.

Lessons learned

Identification of requirements

Our observation times should have included night shifts, as during the prototype interviews nurses mentioned that the nursing tasks performed during night shifts were different from those performed during the day.

Development and fine tuning

Comparable projects should not only determine the information organization based on participants' preferences. Research found that users tend to prefer familiar information organization without being able to predict with which devices they might perform better.[68] Instead, in comparable projects users might be asked to perform key tasks with prototypes and the selection for an information layout might be based on their performance.

To get more generic feedback, one round of prototype interviews might have been based on participatory design. Participatory design would have allowed nurses to draw their own additions and corrections on prototype copies and might have lead to more intensive brainstorming and a higher involvement of the participants. [134]

To reach a higher initial intuitiveness and information extraction during earlier stages in the development process, human factors principles should have been followed closer. During prototype interviews, a scribe could have captured more nuances and allowed for a more fluent process, or cameras could have been used to capture facial expression of the interviewee. Recognition speed could have been measured and compared using computer based evaluation tools.

Validity might be increased through validated questions, checking that users participate only once during the development process, and preventing participants from cooperation when completing questionnaires.

Evaluation

Evaluation sessions could have been recorded to allow later analysis of the nurses' comments and their actions. This might have allowed the identification of possible improvements for the evaluated displays, and additional investigations after the test.

To increase nurses' familiarity with displays and to lead to more generalizable results, nurses could have practiced with all displays prior to the test. To allow more realistic time measurements, computer based prototypes could be used instead of paper prototypes. To decrease variability of the results, the function of the hourglass could be explained to the participants prior to the test, or another possibility to simulate time pressure could be used.

Possibly a more in depth review of test questions prior to the evaluation study might have allowed to identify tasks which are preformed less frequently by nurses such as medication interaction- a task which is normally performed by pharmacy and only in emergency situations by nurses.

To allow the calculation of summed sub scales for workload with a higher validity, participants could be asked to weight sub scales during the test.

Implications for practice

In the following, the implications of our findings for patient safety, productivity, nursing practice, education, and research are discussed.

Patient safety

Nurses' higher level of situation awareness and faster response time might mean that using integrated displays could improve patient safety. Researchers observed eight clinically important medication errors per day in ICU units.[135] If we assume half of these errors were due to nurses' work, and use of the integrated display could prevent the same error rate as in our evaluation (40%, see Table 18), two clinically significant errors could be prevented daily, which might increase patient safety by far.

Productivity

Nurses' faster response time using the integrated display might imply that integrated displays accelerate decision making. If our time measurements were representative such displays might save 124 or 2 min/ hour, see Table 24. This assumes that the evaluated time differences for tasks (Table 21) are representative for the nursing task categories we observed (Table 1) if reduced approximately 30%.[113] This implies that the use of an integrated display could possibly speed up nurses' decision making and help them save time.

Integrated information displays might additionally reduce travel time and data to remember, increase productivity and prevent nurses from memory lapses.

Table 24 Potentially saved time per hour through the clinical use of integrated displays

Task category and scenario	Observed hourly frequency	Average time difference between display conditions per task, reduced by 30%[113] (sec)	Saved time per hour (sec)
Medication management	5.7	6	62
Patient treatment	5.3	2	11
Team communication	8.6	6	50
Total			**123**

Integrated information displays allow easier access to information and could therefore reduce nurses' cognitive overload. Figure 18 shows an example of reduced ways using the example of medication management. Nurses who currently need to travel five ways to obtain all information and the medication would hypothetically only need to travel two ways when using the integrated display. Lapses occur while the operator's attention is diverted and they forget their goal in the middle of a sequence of actions. A nurse could forget, while traveling, what he/she was looking for. Such lapses have been observed by Potter et al.[125]

Nursing practice

The high number of errors which we found should not translate directly into everyday clinical practice – they were more complex than patients ICU nurses might normally treat. The questions were deliberately created to be complex with a high number of simultaneous medications, multiple screens to look at and

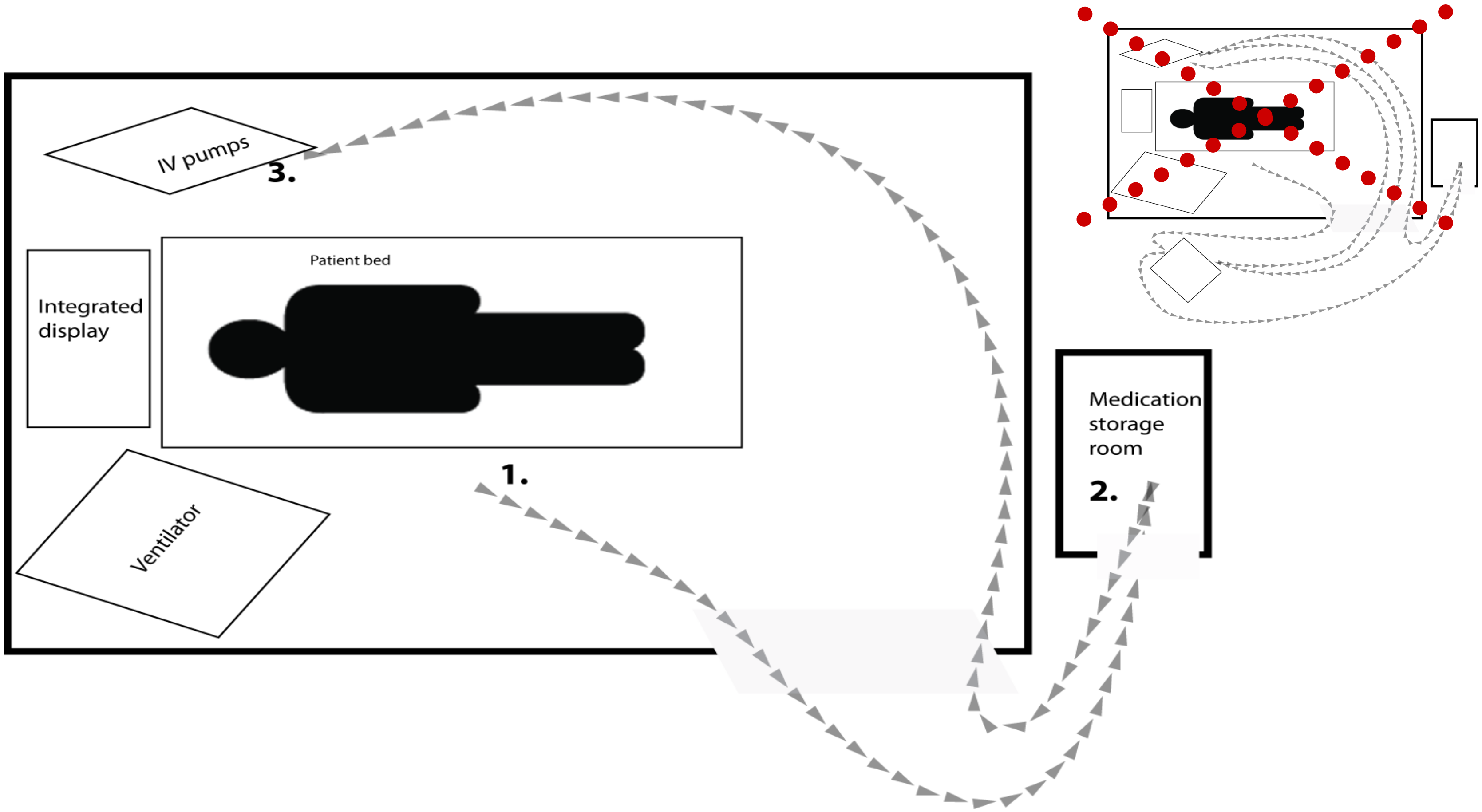

Figure 18 Example of new information flow through the integrated display during medication administration. Ways traveled are reduced from 5 to 2 which might free up time for patient care

addressing information presentation deficits in the Control devices. (see Chapter 5 Methods for more detail). As such, in medication management more than half of the participants failed to identify a continuous medication which needed to be given alongside with two scheduled medications (Table 19 element A2) – possibly because it was displayed on the bottom of the second screen of the electronic medication record and looked comparable to a running medication. Another example for extensive information lookup could be that nurses failed to identify IV incompatibility of two new medications with 6 current, scheduled and PRN medications (Table 19 element A4).

Education

A display which is intuitive to use and easy to understand might mean that less time can be spent explaining the display, allowing a more effective education for nurses. This could help to prevent errors based on not understanding values shown on the display. Functionality which might increase the educational benefit of such a display when implemented is discussed in the future research section, e.g. step-by-step instructions for rate procedures, improved communication with distant monitoring clinicians, and decision support.

For research, our findings expand the knowledge to ICU nurses that integrated information can increase situation awareness and decrease response time. Our findings might imply that future design of information displays for nurses could aim to integrate information from different sources into a single location – but could possibly work on the content and representation of the information (see future work section).

For designers, implications could be to focus on the early integration of human factors design principles[7, 47, 48] to improve correct extraction of information and intuitiveness from the start.

Future research could expand upon our findings by enhancing integrated displays and performing more evaluations.

Future work

The future of displays for monitoring systems for nurses will depend on research such as described in this dissertation. The future ICU room might feature integrated displays with connected devices that do not have their own screens. Decreasing screen prices might result in extra large displays which cover large surface areas, e.g., whole walls. However, such large surfaces might lead to new problems such as unawareness of information due to limited peripheral perception, or information overload because of cluttered integrated displays. Nevertheless, support of team communication, e.g., with distant monitoring clinicians, and awareness of information will be essential and safety critical pillars of future patient care and distant monitoring.

Future research could evaluate more functions of the integrated display, such as messaging and titration of medication, as well as interaction with the display. Messaging envisioned that users could share display content through drag-and-drop, directly communicate, and sending messages. Titration of medication was thought to allow users to better see the effect of medication on vital signs, and to base their decision on changes in the medication administration rate on the trend and previously given medication rate. Interaction with the integrated display would require an interactive prototype in a setting with bidirectional communication of devices (e.g., IV pumps and monitors).

Fallback strategies for possibly unavailable data which is normally shown and essential for nurses' decision processes could be identified. As the integrated display combines data from sources with uncertain technical reliability - such as data from medication databases through the internet – nurses need to have access if these sources are temporarily unavailable. Future research could identify fallback mechanisms to assure nurses' information support even when required resources are not available, e.g., medication compatibility in case the medication database is not accessible.

Display evaluations could be performed at other environments, include participants with different roles, include remote monitoring settings, use eye tracking and session recording, and heuristic evaluation.[48, 136] Additional environments could be included such as fidelity simulators and in the actual context of work[61] - the bedside. The inclusion of other nurses or clinicians would increase the generalizability of the evaluations. Additionally, as the number of virtual ICUs and distant monitoring sites are expected to increase in the future,[137] evaluations testing communication with distant monitoring clinicians could be performed. Evaluations using eye tracking could allow improvements of display elements by analyzing the information participants are looking at. Recorded sessions could be analyzed to determine if participants might have seen the correct answer or if the information presentation might be suboptimal. Usability heuristics could be used to detect – and later correct - usability problems which might not be detected during evaluation with nurses.

Refinement of the display could focus on supporting other nursing tasks and roles as well as other critical care employee roles. Our research has mainly focused on supporting medication management, patient awareness, and team communication. Other research could focus on charting from the bedside to identify options and improvements of the charting process which the integrated data presentation might allow. In our display, charting was only added as an option, but not tested, as we envisioned that a screen of the nurses charting system could be shown and used on the integrated display. Furthermore, future research might identify specific features of a task list, as nurses use paper-based reminders about tasks during their shifts. Support for other nursing roles, such as low acuity nursing units and outpatient clinics could be identified, and additional display interfaces could be designed for other professions such as respiratory therapists, physicians, and nurses aides.

Other methods of display interaction could be identified. For our development, it was assumed that the display would provide a touch screen interface for user interaction. Other research could focus on voice control and audible communication of integrated information, or could explore further options of urgency and vital sign centered patient care views.

Suitable data communication protocols and system processing architecture need to be identified. Communication protocols should allow immediate and automatic communication with any connected device.[132] To integrate data, bidirectional data communication standards need to be evaluated and possibly refined such as the protocols for Medical Bus Standard,[138] Ethernet, wireless, infrared (IrDA),[139] and fieldbus (CANopen).[140] The optimal system processing architecture should be identified. Possible architectures could be a lightweight client on the display with heavy processing by a server or heavy client on the display with lightweight communication with a server. The main goal when selecting such architecture should be to avoid possible interruptions to the care process and danger to the patient. Therefore integrated displays should keep functioning despite interrupted network connectivity, and heavy clients might be advantageous.

Rules to adapt the display content to the needs of the users who are close to the display need to be identified. Sometimes more than one user is in the room, or users who are not nurses. Situations could be that multiple nurses are in the same room, but have different patients and therefore all need to be aware of alarms from their different patients. Another scenario might be that users with different roles are in the room such as a nurse and a physician, or multiple users during rounds. Future research might identify information needs during such scenarios and define possible display content depending on the scenario. Additionally, the feasibility of detection mechanisms to identify the users in the room could be researched, such as radio frequency identification tags(RFID).[141]

Visualizations and rules to connect additional devices to integrated displays could be researched. Additional device could be either more devices from the same kind, such as multiple infusion pumps, or newly developed devices. For many connected devices, the modular approach of our integrated display permits the up- or downscaling of single device representation dependent on the number of connected devices. For newly developed devices data visualizations need to be developed which are easy to understand and blend into the integrated display. Additionally, rules should be defined to determine the size of visualizations based on the importance of the device and the users' information requirements (visible from far away or close up). However, the primary goals should always be to satisfy the information requirements for nurses' situation awareness and maintaining intuitiveness and usability.

Conclusion

The user centered design approach lead to an intuitive display with which nurses had a higher situation awareness and user satisfaction, and a faster response time and workload compared to the displays they currently use. The integrated information display reduces the number of devices nurses need to look at to obtain the information needed to complete their tasks.

Using such an integrated display might lead to better care, fewer errors, and help the patient to get the right therapy at the right time. Although integrated information displays have great promise, technological factors must be addressed if these displays are to achieve their potential for improving patient safety. Future research is needed to further adapt such displays to the needs of critical care.

APPENDIX A

QUESTIONS TO ASSESS PATIENT SAFETY TASKS

Questions to identify patient safety relevance

Questionnaires used a 7-point Likert scale from 1(very important) to 7 (not important), where nurses were asked to indicate the safety relevance of the following tasks.

Items included in the questionnaire are given in the following.

- Rounds
- Drawing blood
- Suctioning
- Keeping notes e.g., of patient values or tasks that need to be done
- Communication with doctors about orders
- Bathing
- Feeding
- Patient assessments
- Monitoring patients Sp02
- Monitoring patients trends (development over 24 hours)
- At a glance assessments
- Monitoring correct position of ventilation tube
- Breathing trial
- Ventilator check
- Monitoring wound status
- Monitoring vitals

- Monitoring Medication
- Double checking medication (right order, right medication)
- Preparing medications
- Administering medications
- Monitoring urine output
- Charting
- Oral care
- Communication with other nurses about patient
- Communication to organize procedure
- Communication with doctor about patient
- Communication with pharmacy
- Communication between nurse and RT about patient
- Communication with patients family about patient
- Communication with patients
- Setting up equipment
- Assessing reasons for alarms
- Knowing my critical patients values when in another patient’s room
- Knowing reasons for alarms of my patients when in another patient’s room

APPENDIX B

QUESTIONS USED TO MEASURE INTUITIVENESS AND CORRECT EXTRACTION OF INFORMATION

Questions to measure intuitiveness

Which element shows the ventilator settings?

Which element opens the charting screen?

Which element opens communication screen?

Which element increases displayed information on the whole monitor?

Which element shows the fluid balance?

Trending

Which element opens the trending screen?

Which element shows the MAP trend?

Which element shows the medication trend?

Which element changes the trend duration to 1hr, 2hr, 24hr?

Which element shows HR alarm settings?

Medication management

5 questions asking to identify current medication, PRN medication, scheduled medication, time until current medication is empty, and medication infusion rate.

“Element X is showing:” 4 possible answers

Which element shows the doctor’s order?

Which element shows additional information?

Which element sets and gives a bolus?

Which element changes the medication titration rate?

Which element is for reordering the medication?

Questions to measure reading accuracy

2 questions asking about an alarm in the nurse's second patient:

Which patient bed is currently alarming?

Which value is currently alarming?

Fluid balance

"The fluid balance of the last hour is:" (4 choices)

Trending

4 questions asking about a past vital sign value and medication rate:

What was the HR at 15:20 / 06:30?

What was the rate of NOREPI at 13:00 / 06:30?

What are the current HR alarm settings?

At what time did the MAP exceed the alarm limits?

Medication management

3 questions asking about time until current medication is empty:

"Element X is showing:" (4 choices)

When can the next dose of Fenoldopam be given?

When does Pentothal need to be given.

APPENDIX C

SCREENS OF THE FINAL PROTOTYPE

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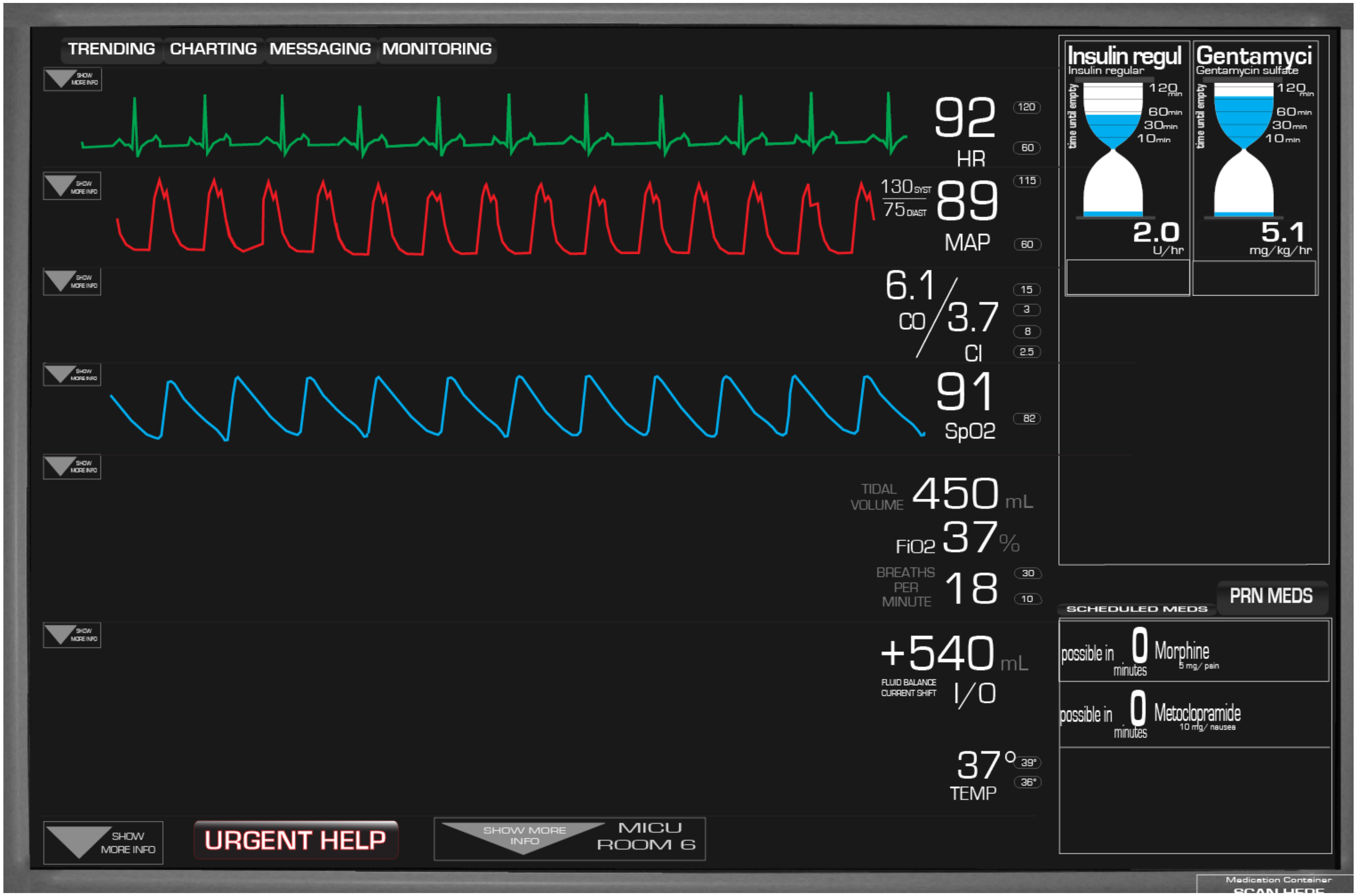

Figure 19 Main screen showing PRN medication

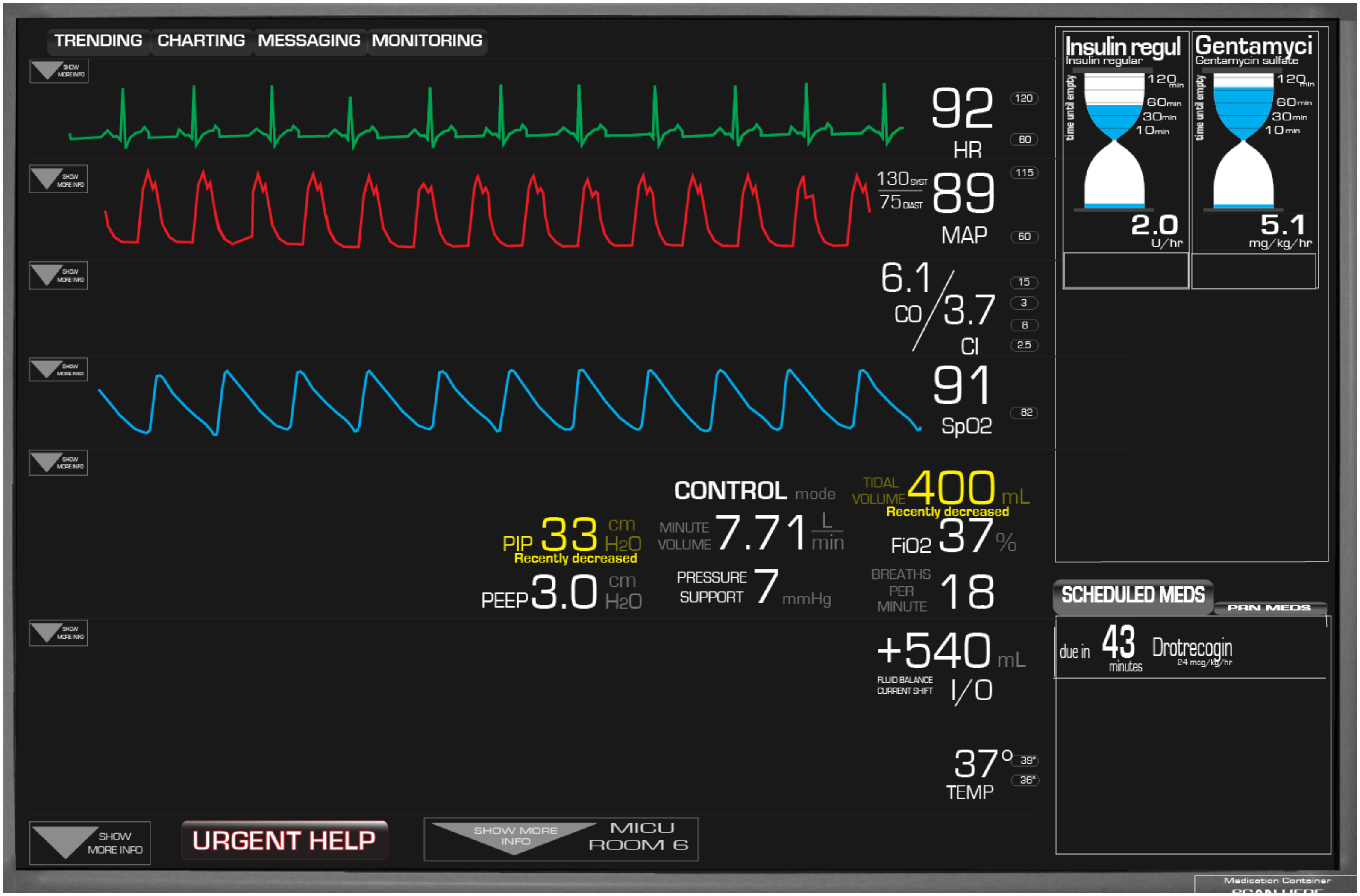

Figure 20 Changed ventilator settings and scheduled medication

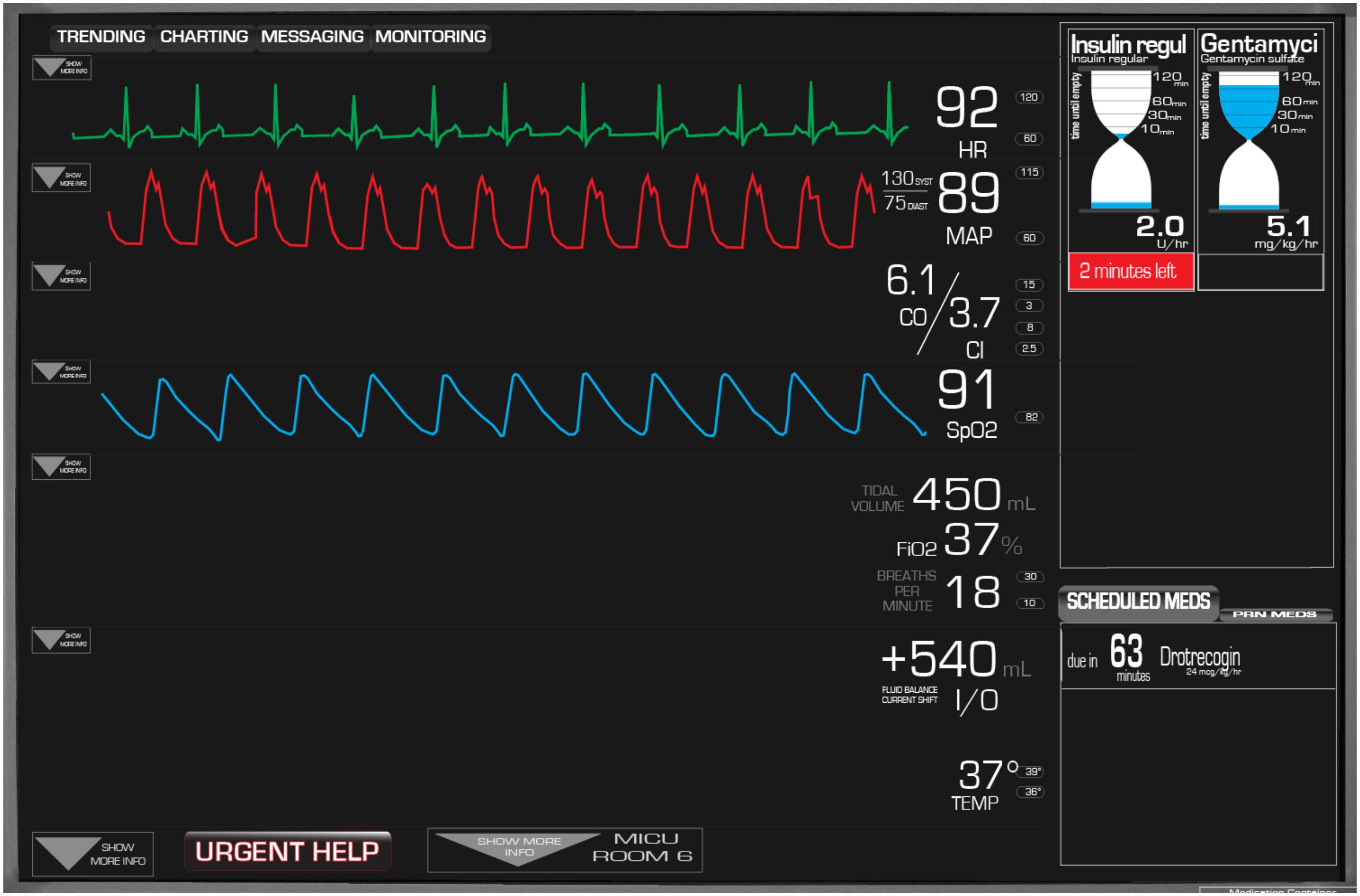

Figure 21 Current medication empty

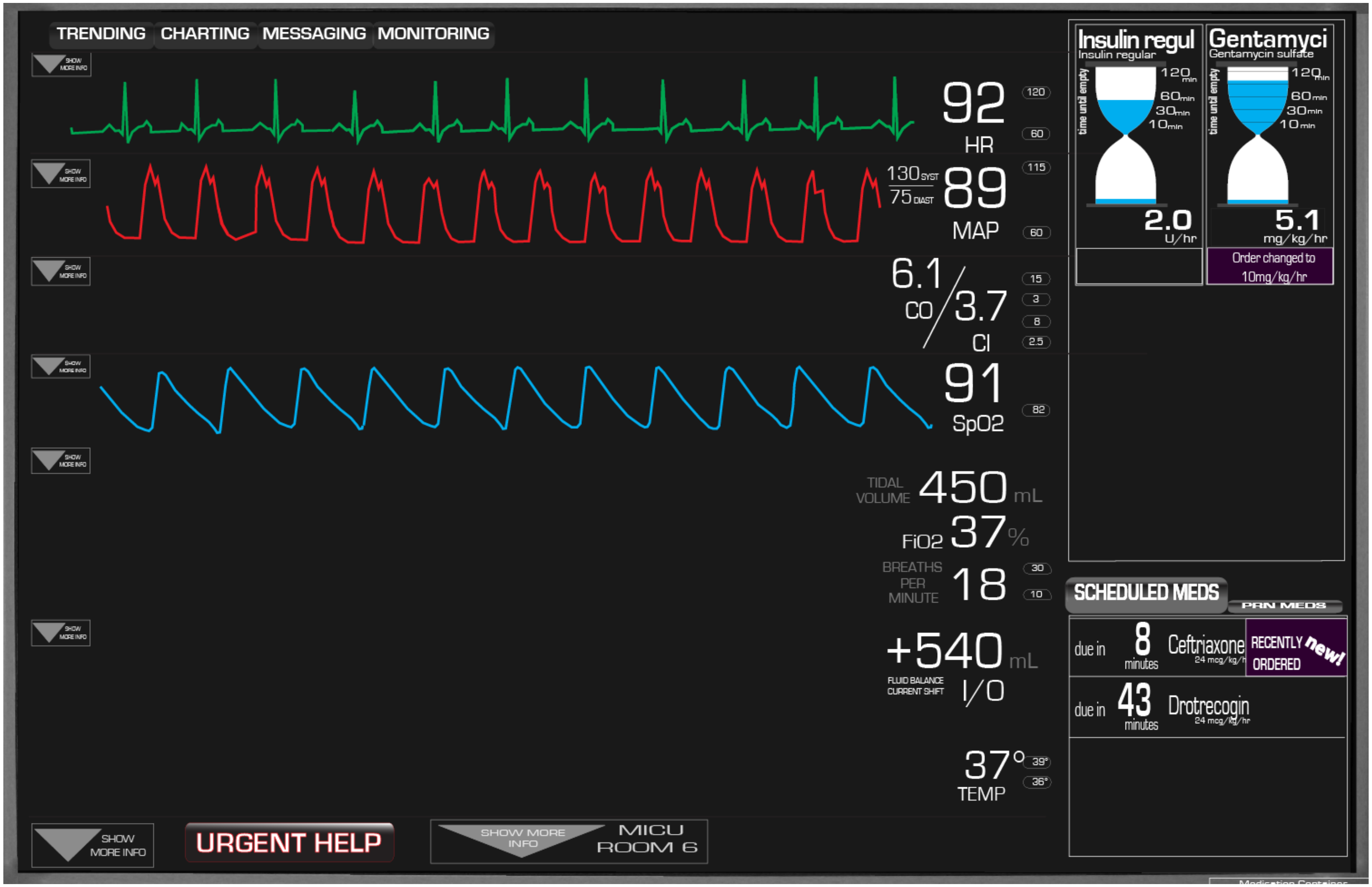

Figure 22 Changed current medication orders and new scheduled medication

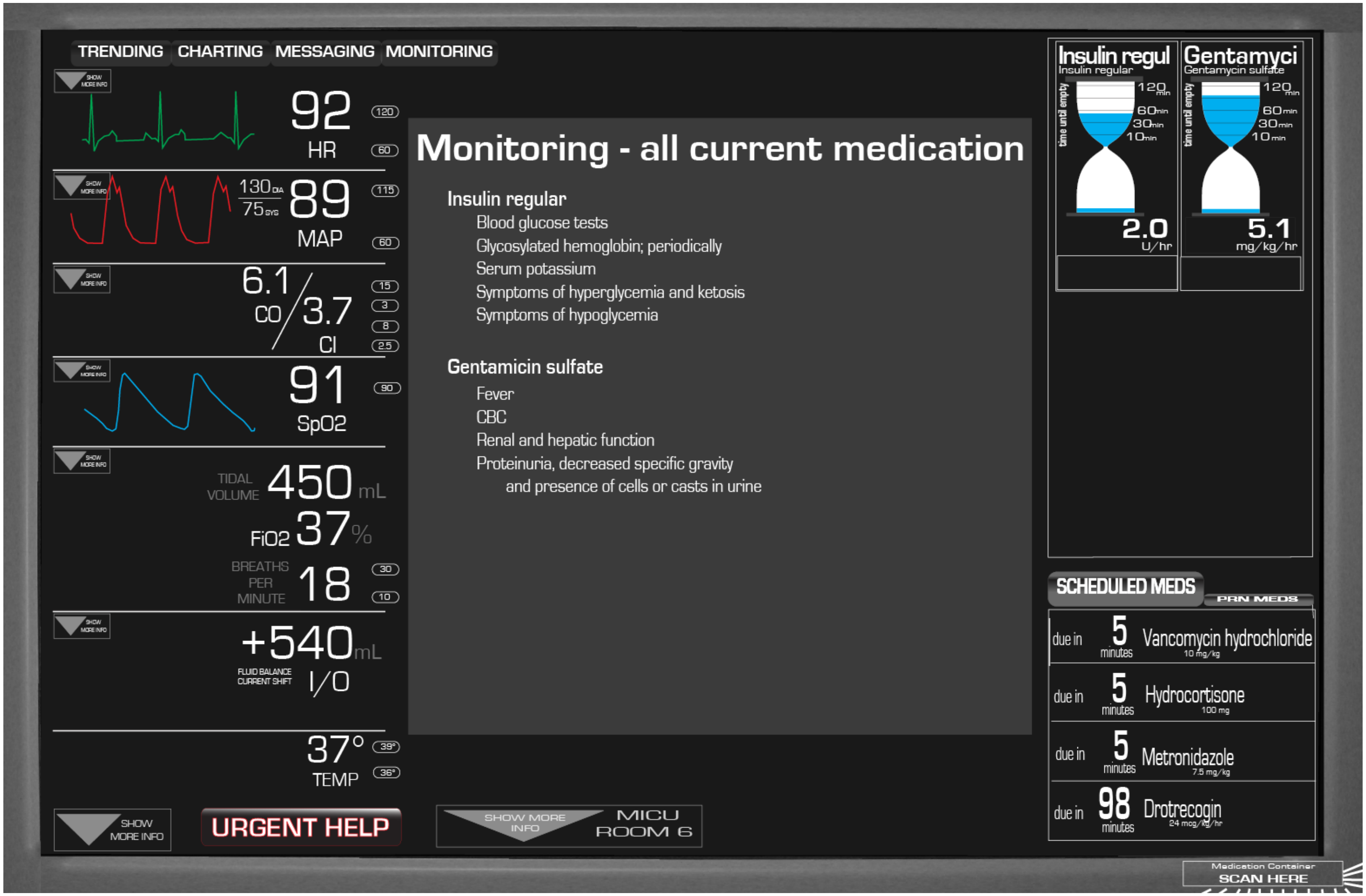

Figure 23 Monitoring requirements for current medication

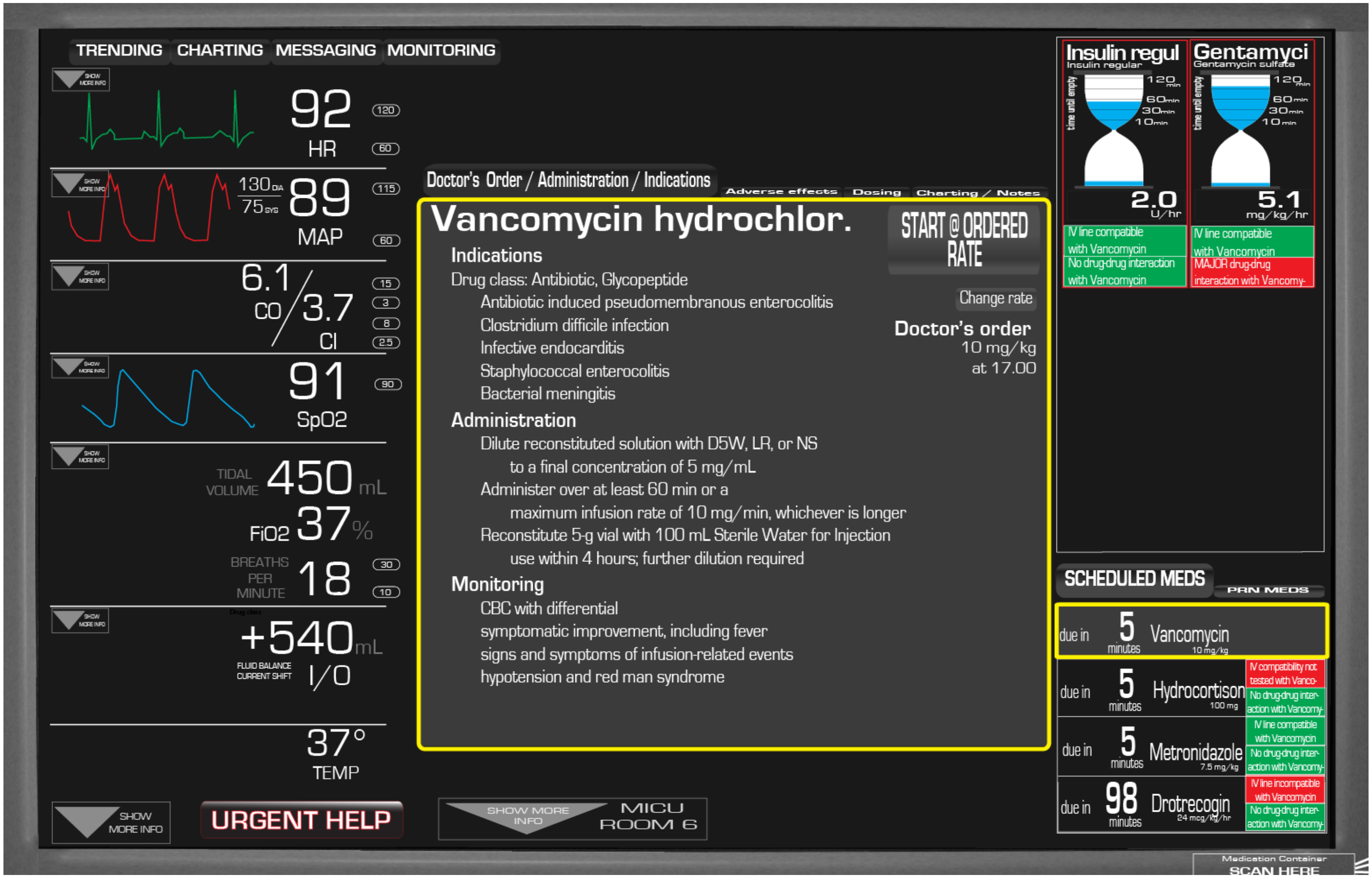

Figure 24 Additional medication information for Vancomycin. Adverse effects, indications, instructions for administration, and monitoring requirements

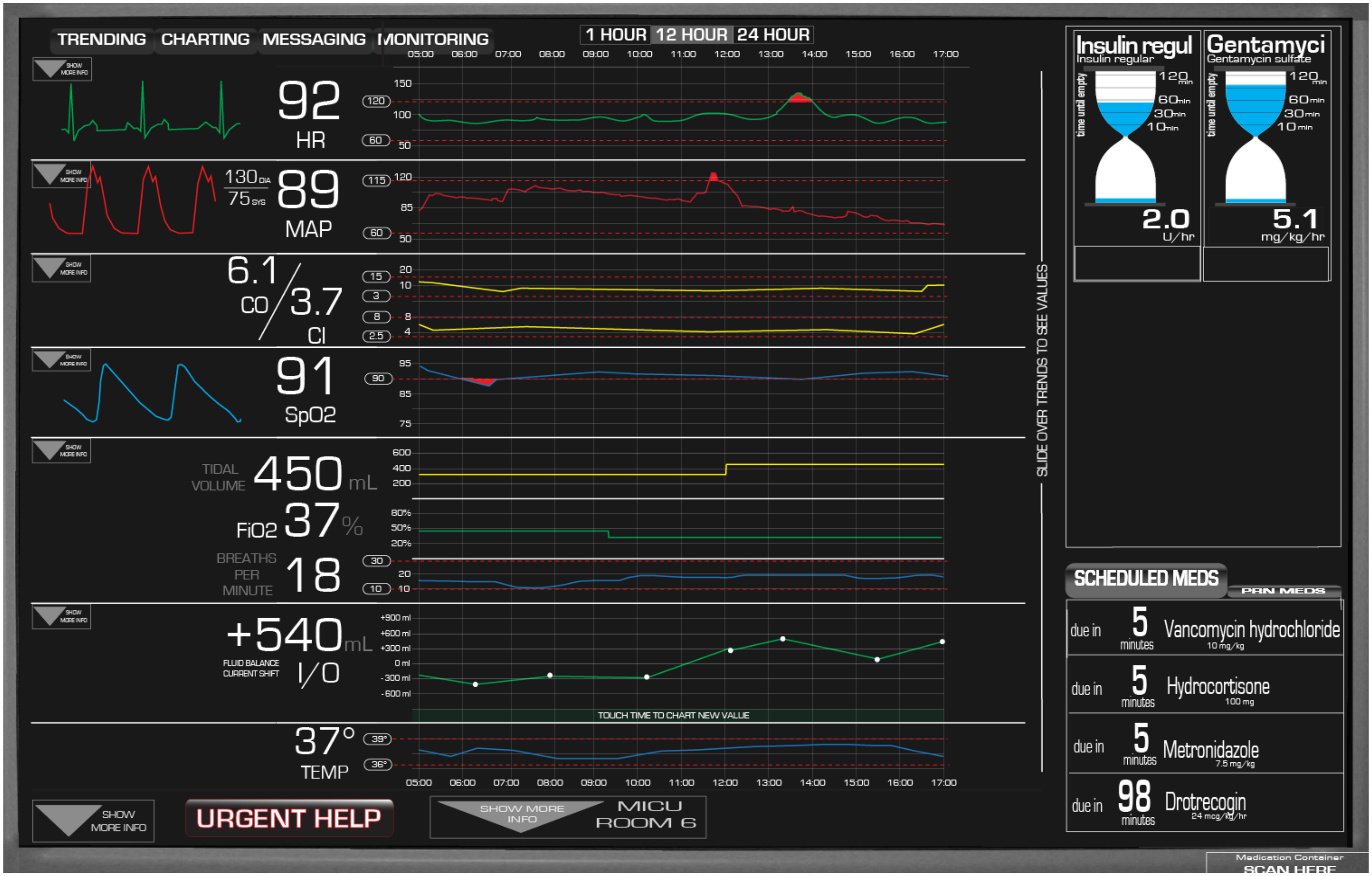

Figure 25 Vital sign trending – no medication trend shown

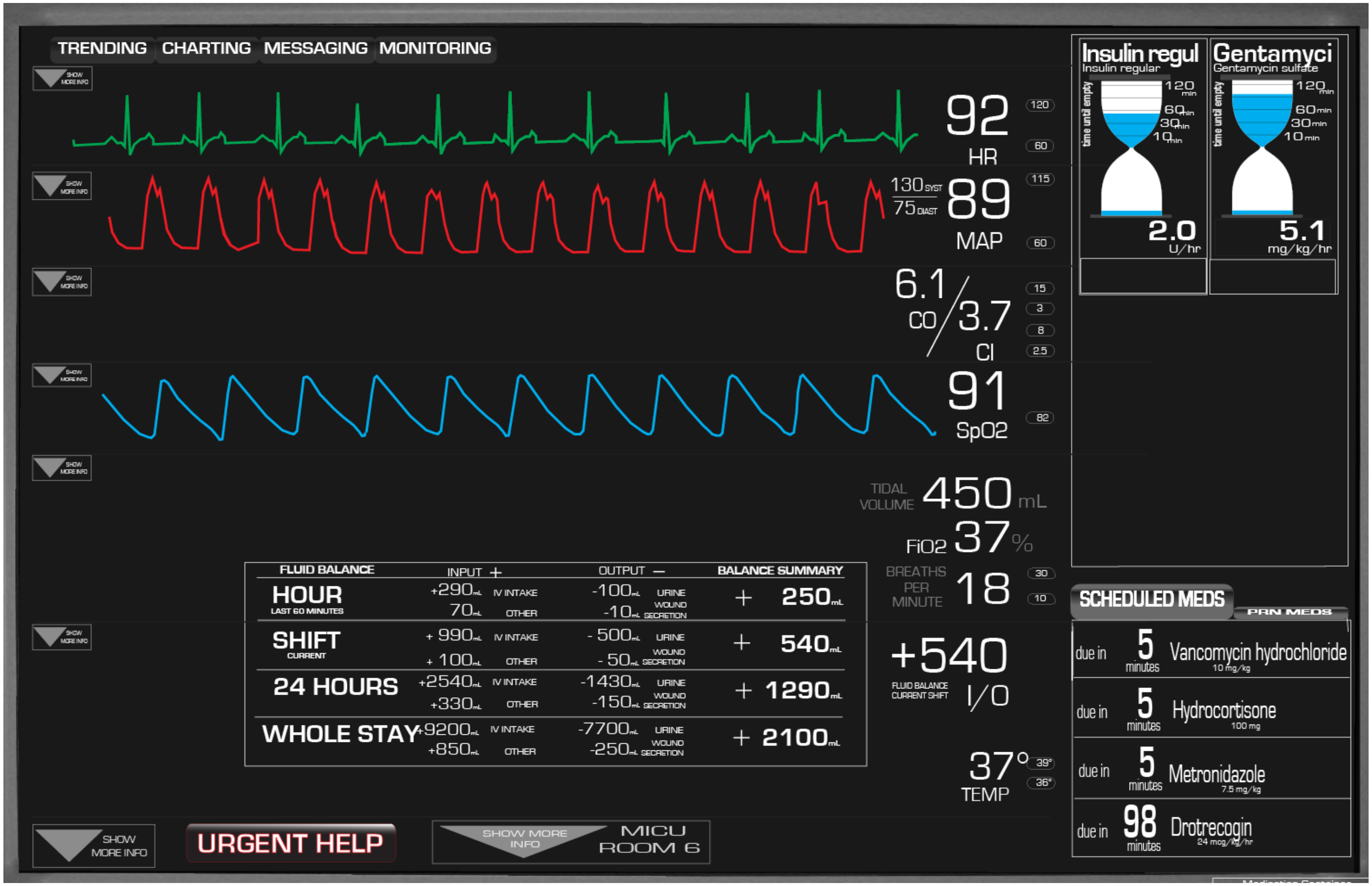

Figure 26 Fluid management

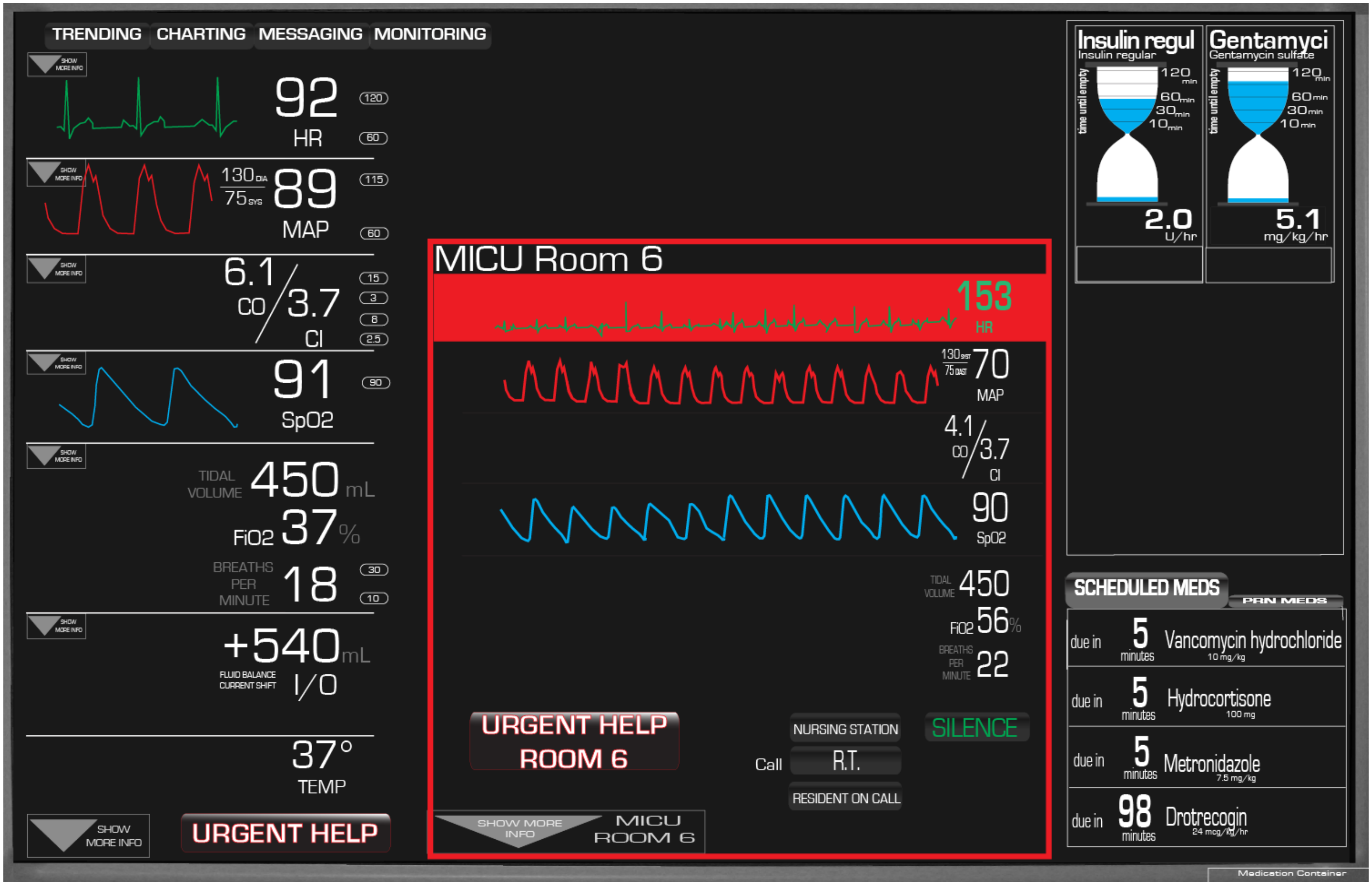

Figure 27 Alarm in the other patient's room

APPENDIX D

SCENARIOS AND QUESTIONS TO MEASURE

SITUATION AWARENESS

Scenarios and questions to measure situation awareness

The correct answer is indicated for each display, for the Integrated display with (in) an for the Control displays with (co).

Medication management

Please read the following scenario and then click OK to see the first question. In case you need some additional information which is not given, please let us know.

A colleague swamped with work asks you for a favor. She says “Would you give the patient in room 8 his medication for me? He had a car accident and is septic. He just came in from the floor and does not have a central line but has two 18 gauges peripheral lines. Meds are infusing in each line.”

<u>Perception</u>

Now you are with your colleague's patient and see the screen(s) of this patient. Which of the following medications are currently being administered in the two 18 gauge lines?

- Hydrocortisone and Vancomycin (co)
- Hydrocortisone and Gentamycin
- Insulin and Gentamycin (in)
- Insulin and Drotrecogin
- None of the above
- Do not know

Perception

Please check which medications need to be administered within the next 5 minutes.

- Vancomycin, Hydrocortisone, Metronidazole (i)
- Vancomycin, Hydrocortisone
- Gentamycin, Metronidazole, Drotrecogin (co)
- Gentamycin, Metronidazole
- Ceftriaxone, Hydrocortisone
- Do not know

Control – projection

The attending is concerned that pharmacy has not checked drug-drug interaction for Gentamycin as the order was rushed. To protect your patient: Do you expect future drug-drug interaction while administering Gentamycin together with the currently infusing meds (Hydrocortisone and Vancomycin)?

Integrated – projection

The attending is concerned that pharmacy has not checked drug-drug interaction for Vancomycin as the order was rushed. To protect your patient: Do you expect future drug-drug interaction while administering Vancomycin together with the currently infusing meds (Insulin and Gentamycin)?

- Drug-drug interaction of Vancomycin and Hydrocortisone
- Drug-drug interaction of Hydrocortisone and Gentamycin

- Drug-drug interaction of Vancomycin and Gentamycin (co)(in)
- Drug-drug interaction of Metronidazole and Gentamycin
- None of the above
- Do not know

<u>Control – projection</u>

You decide to administer Metronidazole and Drotrecogin together with the currently infusing meds (Hydrocortisone and Vancomycin). However, as the patient has only 2 lines you need to decide which of the lines to use. For which of the following medication combinations do you expect to see IV in-line incompatibility? Assume that not tested meds are incompatible.

a) Vancomycin - Drotrecogin

b) Vancomycin - Metronidazole

c) Hydrocortisone - Drotrecogin

d) a and c (co)

e) None

f) Do not know

<u>Integrated – projection</u>

You decide to administer Hydrocortisone and Metronidazole together with the currently infusing meds (Insulin and Gentamycin). However, as the patient has only 2 lines you need to decide which of the lines to use.

For which of the following medication combinations do you expect to see IV in-line incompatibility?

a) Hydrocortisone – Furosemide
b) Hydrocortisone - Gentamycin (in)
c) Metronidazole – Insulin
d) a and b
e) None
f) Do not know

Control – comprehension

In the end you decide to wait to administer meds. Which of the following side effects of the currently administered medication Hydrocortisone and Vancomycin would expect to see and monitor?

Integrated – comprehension

In the end you decide to wait to administer meds. Which of the following side effects of the currently administered medication Insulin and Gentamycin would expect to see and monitor?

- Mental / neurological status and hypoglycemia (in)
- Fluid balance and signs and symptoms of ototoxicity (co)
- Signs and symptoms of bleeding and fluid balance
- Improvement in nausea/vomiting and symptoms of hypoglycemia
- None
- Do not know

Comprehension

The patient says he has nausea and pain - please push a PRN medication. What issues are you most concerned about in this situation?

- Morphine can be given (co)
- Metoclopramide can be given
- Both PRN medications can be given (in)
- No PRN medication can be given
- Do not know

Patient awareness

Please read the following scenario and then click OK to see the first question. In case you need some additional information which is not given, please let us know.

You just received shift report from the night shift and you are ready to round on your two patients. In the report you heard that your first patient had several short runs of PVCs and your second patient in the room next door had episodes of dangerously low BP during the night shift. You enter your first patient's room and set the monitor to optionally show the screen with values from your second patient.

Perception

You are with your first patient. Which is the most recent alarm caused by a vital sign being too high or too low?

- HR (in)
- ECG
- SpO2 (co)
- MAP
- VTACH
- Do not know

<u>Control- perception</u>

What was the first patient’s HR at 13.45?

- 121
- 105
- 99 (co)
- 89 (in)
- 52
- Do not know

<u>Integrated – perception</u>

What was the first patient’s HR at 13.00?

- 121
- 105
- 99 (co)
- 89 (in)
- 52

- Do not know

Projection

Based on the SPO2 value during last HR alarm: What would you expect the first patient’s SpO2 level to be if there was another HR alarm in the future?

- Adequate - above 90
- In-between - about 90 (in)
- Inadequate - below 90 (co)
- Do not know

Projection

Based on your patient’s fluid balance the last 24 hours, how do you expect your patient’s fluid balance to develop?

- Assume that intake and output will stay the same.
- Will have increased negative balance (co)
- Will have neutral balance
- Will have increased positive balance (in)
- Do not know

Comprehension

Over the last 24 hours, what type of intake contributed mainly to your patient’s current fluid balance?

- Sodium chloride

- IV intake (in)
- Fresh Frozen Plasma (co)
- Oral intake
- Parenteral flushes
- Do not know

Comprehension

You hear an alarm from the room of your second patient next door and wonder what's causing it. However, you are currently suctioning your first patient's airway and cannot leave the current room.

What do you think is causing the alarm?

- Increased HR (in)
- Decreased HR
- Decreased SpO2 (co)
- Decreased MAP
- None of the above
- Do not know

Team communication

Please read the following scenario and then click OK to see the first question. In case you need some additional information which is not given, please let us know.

You need to leave the ICU abruptly to take your first patient to Radiology.

You plan to ask a colleague to cover your second patient and want to tell her what to do in the next 20 minutes. Please base your answer on the display(s).

<u>Projection</u>

What tasks would be due while you are gone for 20 minutes?

- Insulin will run out in 2 minutes (in)
- Order was changed for Metronidazole
- Order was changed for Morphine
- Hydrocortisone will run out in 17 minutes (co)
- None of the above
- Do not know

<u>Control - projection</u>

When do you expect Vancomycin about to be empty?

- 20 hrs (co)
- 10 hrs
- 100 minutes
- 30 minutes
- 2 minutes
- Do not know

Integrated - projection

When do you expect Gentamycin about to be empty?

- 20 hrs
- 10 hrs
- 100 minutes (in)
- 30 minutes
- 2 minutes
- Do not know

Perception

After coming back from Radiology, your colleague tells you that while you were busy the Pulmonary Fellow was in one of your patient’s rooms. You decide to check this patient’s ventilator. Which ventilator setting was recently changed?

- Tidal volume and PEEP (co)
- Tidal volume and PIP (in)
- SpO2 and VTe
- CMV and PEEP
- Nothing was changed
- Do not know

Comprehension

How did the fellow change the ventilator settings?

- Tidal volume was recently increased (co)

- PIP was recently decreased (in)
- CRAP was recently changed
- None of the above
- Do not know

Perception

Was there any medication recently ordered?

- Furosemide was recently ordered (co)
- Ceftriaxone was recently ordered (in)
- Drotrecogin was recently ordered
- Hydrocortisone recently ordered
- Nothing recently ordered
- Do not know

APPENDIX E

ANSWERS TO FREE TEXT QUESTIONS

Table 25 How was the availability of clinical information?

Control setting	Integrated display
Had to search around for some of the information.	It was extremely readily available. Would love to be able to use these monitors.
available but not interfaced	very easy to find the information that i needed
good- just a lot of papers to go through	available
The final task was difficult to complete within the time constraints i.e., looking at many medications and the compatibilities/interactions sheet. Otherwise ok.	Good.
available but at times difficult to obtain/locate	easily accessed
poor info on drug interactions- side effects	improved compared to other display
available- but not easy to find or combine information	great. It is very helpful to have all different kinds of information available from one source- instead of having to look several different places and compare.
it was there just hard to find especially with Micromedex	it was easy to find
Good- getting used to format was challenging.	Good. Quite intuitive in its operation.
information was available- if you knew exactly where to look.	vary available. It would put all of the information at your fingertips and at the bedside where it is needed the most.
Good	good
Very available	Adequate

Table 26 How was your overall sense of the patient and the treatment?

Control setting	Integrated display
Could have been made more easier- with a better flow of computer programming.	Pt care would be greatly increased due to the fact all the information is in the room and available to you right there.
good	very good
spread among screens	great
The patients were ok but I would have delegated another nurse to check on pt #2 to make sure nothing bad was happening where I could not attend to them	ok
adequate could have been better	felt like I knew what was going on and information was easy to access
inadequate	improved compared to other display
it would take a while of sitting and reviewing all of the information to get a good sense- I did not have a great sense of pt from just looking over briefly	much easier to get an overall impression of the patients treatments and condition with all information available at a glance
good- just more time consuming	the information is awesome and its easy to find
Good	I feel I had a complete overview of patient care requirements and information availability.
Felt like there was frequent periods of wasted time looking for the information to make an informed decision.	I felt like I had the information I needed to make the best informed decision.
Good	Good
I felt like I had a general idea of the patient and their current condition.	I think it is always challenging being given a brief history and not being able to visualize a patient. Especially in the ICU setting- as a nurse you are always analyzing the patient first and then the monitor. It was a little bit of a departure looking solely at monitor vitals. Yet- it was easy to grasp the over all condition.

Table 27 What did you like best?

Control setting	Integrated display
The IV pumps.	The display and the ability to see medications- changes- ventilator changes and IV medications.
like the pictures of the pumps	liked how easy it was to find the information that i need and how fast i could find that info
	seeing the meds/vent settings/I&O
2 patient views on bedside monitor- alarm reviews- pump time remaining on drugs	How easy the system was to use.
visual	the wide variety of information that is available
outlook- eMAR	availability of information
the eMAR with PRN meds- last given- is easy to understand.	having all information available in one place- especially medications running- due- and compatibility on the room monitor.
eMAR is OK with PowerChart	the iv compatibilities in the room
Taking part in something new.	Information availability at bedside is amazing.
none.	availability of information.
familiar	Having everything right their in front of you.
I enjoyed the availability of the IV compatibility to reference when administering medications	IV compatibility on the monitors

Table 28 What should be redesigned?

Control setting	Integrated display
The monitor.	nothing.
the time limit lengthen felt rushed looking up info on a few questions	nothing looks good
interfacing	?
none	Drug-drug compatibilities and interactions should be a little more clear.
increased clarity and ease with locating information. consolidation into less programs.	do not know
vent face- not user friendly. Micromedex...be able to list all meds together rather than one by one.	more obvious alert system for nurse and physician when drugs are completely incompatible for drug-drug interaction.
The compatibility is easy to use and understand- but takes a lot of review to be sure you have looked at all medications accurately- if this was redesigned to be more efficient and easy to look at it would be nice. Also reviewing vital trends was difficult because the lines do not tell you actual numbers- just areas. I didn't understand the vent change screen- but I do not look at those often because the resp therapists deal with that. If that was changed to more understandable language it would be nice.	nothing
Micromedex information displays	nothing that I can think of until i use it
Have format on computer rather than on paper.	Allow ability to view alarms in rooms other than those of my patients.
POWERCHART.	POWERCHART
Not having every thing in one place makes getting the information more difficult	alarm for other pt should be smaller and go away after a time limit
I really have no suggestions	Intake and output. Knowing exactly what is running and how fast (mL/hr).

APPENDIX F

NASA TASK LOAD INDEX

All following questions use Likert scales 1..20 where 1 = lowest and 20 = highest.

Mental Demand: How much mental activity was required (e.g., thinking, deciding, calculating, remembering, searching, etc.)? Was the task easy or demanding, simple or complex?

Physical Demand: How much physical activity was required (e.g., heavy lifting, pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, restful or strenuous?

Temporal Demand: How much time pressure did you feel during the scenario due to the pace of the scenario demands? Was the pace slow and leisurely or rapid and frantic?

Performance: How successful do you think you were in accomplishing the goals of the tasks? How satisfied were you with your performance in accomplishing these goals?

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Frustration Level: How insecure, discouraged, irritated, stressed, and annoyed versus secure, gratified, content, relaxed, and complacent did you feel during the task?

APPENDIX G

QUIS QUESTIONNAIRE: PART THREE

QUIS consists of twelve parts covering areas from system experience (part one) to software installation (part 12).

Part three covers Overall User Reactions to a system and is described in the following.

Questions ask participants about their impression using the system.

Participants are asked to select a number from 1(terrible) to 9 (wonderful) on six Likert scales. The six high level interface factors measured with the 9-point Likert scales are:

a) Terrible…wonderful

b) Frustrating…satisfying

c) Dull…stimulating

d) Difficult…easy

e) Inadequate power…adequate power

f) Rigid…flexible

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